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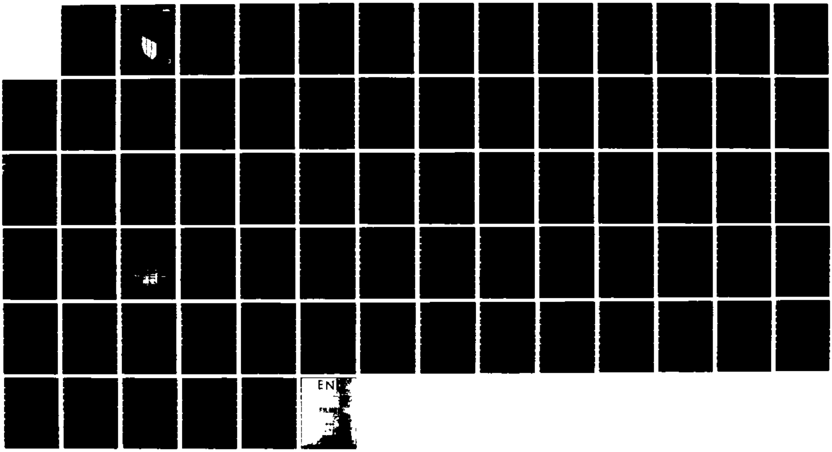

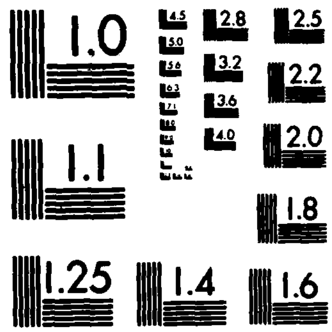

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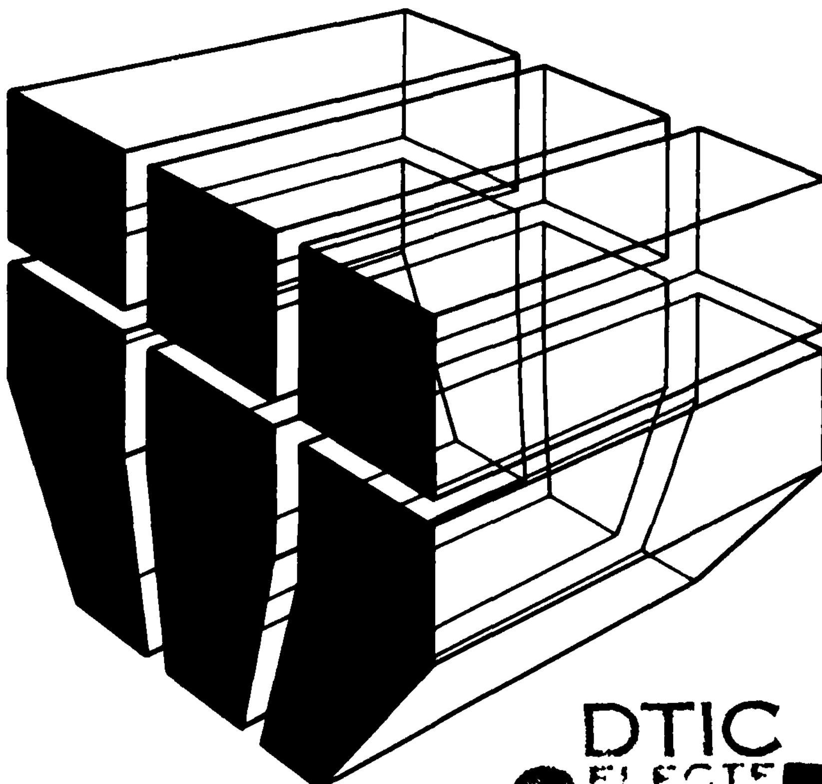
TECHNICAL REPORT N-178
July 1984

NOISE FROM TRAFFIC AND NOISE BARRIER PERFORMANCE: A PREDICTION TECHNIQUE



by
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A procedure for predicting Army vehicle noise and barrier performance is described. This procedure is faster and simpler than existing methods because the calculations deal with pasques--linear quantities--rather than decibels. The equations provided for direct calculation can be programed on small computers for rapid solution, eliminating the table lookups required with decibels. The new procedure can handle more complex sites, yet also enables quick assessment of a situation. This limits unnecessary calculations by screening

BLOCK 20. (Cont'd).

out sites not really in need of noise reduction. In addition, the procedure can predict noise for more vehicle types, including Army tracked vehicles for transporting personnel and weapons.

FOREWORD

This work was performed for the Assistant Chief of Engineers, Office of the Chief of Engineers (OCE), under Project 4A62720A896, "Environmental Quality Technology"; Task A, "Installation Environmental Management Strategy"; Work Unit 029, "Technology to Reduce Noise Impacts of Training Activities." The OCE Technical Monitor was MAJ S.J. Stone, DAEN-ZCE.

The procedure was developed by Ken Eldred Engineering under contract with the U.S. Army Construction Engineering Research Laboratory (CERL). The work was directed by Dr. Richard Raspet of the Environmental (EN) Division of CERL. Dr. Paul D. Schomer, Kevin Stuart, and Joseph McBryan of CERL performed the measurements of vehicle noise and prepared the appendix detailing these measurements. Dr. R. K. Jain is Chief of CERL-EN.

COL Paul J. Theuer is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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NOISE FROM TRAFFIC AND NOISE BARRIER PERFORMANCE: A PREDICTION TECHNIQUE

1 INTRODUCTION

Background

Increased operation of Army tactical vehicles on installations has created noise problems. The noise from traffic can disturb human activities; for example, it interferes with communicating, hearing television, concentrating on tasks, and sleeping.

For existing roads, there are three practical approaches to controlling potential noise impacts: reduction of vehicle source noise, control of land use to prevent incompatible development, and use of noise barriers that break the line of sight between a sound and an observer.

The reduction of vehicle source noise is not usually controllable. Land use control is feasible when a road is being sited; however, when existing roads are bordered with incompatible land uses or new roads must be sited near noise-sensitive uses, the noise barrier is the only method offering significant promise for noise reduction.

Many factors affect the design and performance of noise barriers. Thus, oversimplified or inaccurate prediction schemes can lead to the construction of unnecessary or inefficient barriers. An accurate procedure is needed for predicting vehicle noise and noise barrier performance at Army installations.

Objective

The objective of this study was to develop an accurate procedure for predicting vehicle noise and noise barrier performance.

Approach

Existing prediction techniques were reviewed and their weaknesses were identified. Newer, state-of-the-art prediction methods were incorporated into these schemes. Many tedious table lookups were converted to simple calculations. The key to simplifying these methods was the use of a linear scale for sound exposure. The new technique significantly reduces calculation time and complexity. Measurements made by the U.S. Army Construction Engineering Research Laboratory (CERL) of tracked vehicles were incorporated into the noise prediction data base (discussed in the appendix).

Mode of Technology Transfer

This technical report will be distributed to Army facilities engineers for field use, in conjunction with the Integrated Noise Contour System when the calculation scheme is computerized. When it has been field tested, the information will be incorporated into a new technical manual on noise mitigation. In addition, the procedure developed complements and extends the information in Army Technical Manual (TM) 5-803-2, Environmental Protection Planning in the Noise Environment (June 1978).

2 PROCEDURE DEVELOPMENT

This procedure represents an update of the barrier design methods described in Sections 3.6 and 5.2 of TM 5-803-2. It also provides a methodology that can handle more complex sites than the TM 5-803-2 method, while retaining a "quick" method for an initial screen of the situation. All calculations can be made directly with equations that can be programmed on a programmable calculator or personal computer.

The procedure provides noise information on three types of Army vehicles: trucks, tracked transport carriers, and tracked weapons vehicles. It includes data for medium and heavy commercial trucks and for automobiles while these vehicles are cruising at constant speed and accelerating from a stop. It also contains data and algorithms for calculating the effects of road gradients, the number of vehicles in daytime and at night, dense vegetation, ground absorption of sound, and shielding by terrain or buildings.

Three different levels of complexity are contained in this procedure: (1) Initial Screen, (2) Simple Site, and (3) Complex Site. The Initial Screen method is very direct and simple, involving minimal calculation. However, it should work well enough for screening a large portion of the site situations evaluated. The basic approach in this procedure is to use the Initial Screen to eliminate roadway sections or observer sites from concern and thus minimize needless computation.

The Simple Site method uses a single, straight road segment to model the real roadway. It allows use of a two-way traffic and a symmetrical barrier of finite length. It should be accurate enough for most design situations on Army installations. The Complex Site method models the real road with a series of connected straight line segments. It is able to accurately model curves and hills along the center line of the real road and to reflect the effects of intervening topography on the transmission of sound from vehicle sources to observer sites.

Site Description and Design Goal

Road sections to be investigated should be described as simply as possible. The sites selected preferably should have straight road segments and representative distances and topography between road vehicle noise sources and observer locations. For both the Initial Screen and Simple Site methods, one to three observer sites are typically enough. An observer site is a location at which the noise level and noise reduction are to be evaluated. These should be chosen so that a representative level and reduction are calculated.

The Initial Screen and Simple Site methods use a single straight road segment for a model of the real road. The segment is infinite in length for the Initial Screen method; for the Simple Site method, it should extend to 10 times the distance to the farthest observer location in both directions. (This distance translates into an angular range of approximately $\pm 85^{\circ}$ or a total angle of 170°.) The Complex Site method uses defined segments to account for road geometry in three dimensions and for topographical differences along the road (see Table 4 for a summary of detailed segment criteria). The

Complex Site method should be used when it is necessary to account for intersecting roads. The Initial Screen uses only one direction of traffic flow and cannot consider a significant median barrier. Both of the other methods can consider two-direction traffic flow and evaluate the effects of a median barrier.

Design goals should be based on the land uses found adjacent to the right-of-way. Suggested guidelines for land use compatibility with noise were developed in 1980 by the Federal Interagency Committee on Urban Noise.[1] Similar information is contained in Section 4.5 of TM 5-803-2. These guidelines are primarily stated in terms of the DNL (Ldn in older documents) in decibels. The design goals in this procedure, however, are stated in the equivalent linear scale--the day-night sound exposure in pasques. Figure 1 is an illustration of the relationship between these two scales.

Vehicle Noise Source

There are several prediction methods for the noise from civilian road vehicles.[2] However, most of these methods are based on highway speeds of over 70 km/h. Lower speed data have been developed,[3] with a particularly comprehensive data set developed for the EPA National Roadway Traffic Model. These sources were used to form the data base for civilian vehicles shown in Figure 2. The Army vehicle data shown in Figure 2 are based primarily on another source.[4]

The data show the noise from tracked vehicles to be on the order of 10 times the noise of trucks, and the noise from trucks is approximately 60 times that of automobiles. They also indicate that the noise exposure of civilian trucks and accelerating automobiles is fairly constant below about 70 km/h. This relationship is used in the noise approximation for the Initial Screen method.

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[1] Guidelines for Considering Noise in Land Use Planning and Control (Federal Interagency Committee on Urban Noise, June 1980).

[2] T. M. Barry and J. A. Reagan, FHWA Highway Traffic Prediction Model, FHWA-RD-77-108 (December 1978); G. S. Anderson, et al., Manual for the Prediction of Surface Transportation Noise and Its Control Through Facility Design, Alberta Surface Transportation Noise and Attenuation Study (January 1976); B. A. Kugler, Design Guide for Highway Noise Prediction and Control, NCHRP Report 3-7/3 (TRB National Research Council, November 1974); G. S. Anderson, et al., West Side Highway Project: Final Technical Report on Noise, BBN Report 3362 (March 1977); F. F. Rudder, National Roadway Traffic Noise Exposure Model (U.S. Environmental Protection Agency, 1979); J. D. Allen and M. D. Kurre, The Automobile as a Component of Community Noise (Battelle Columbus Laboratories, June 1980); J. D. Allen and M. D. Kurre, The Contribution of Medium and Heavy Trucks to Community Noise on a National Scale (Battelle Columbus Laboratories, March 1981); N. P. Miller, A Method for Assessing Automobile Noise (BBN Report 4370, June 1980).

[3] G. S. Anderson, et al., 1977; F. F. Rudder; J. D. Allen and M. D. Kurre, 1980 and 1981; N. P. Miller.

[4] TM 5-803-2.

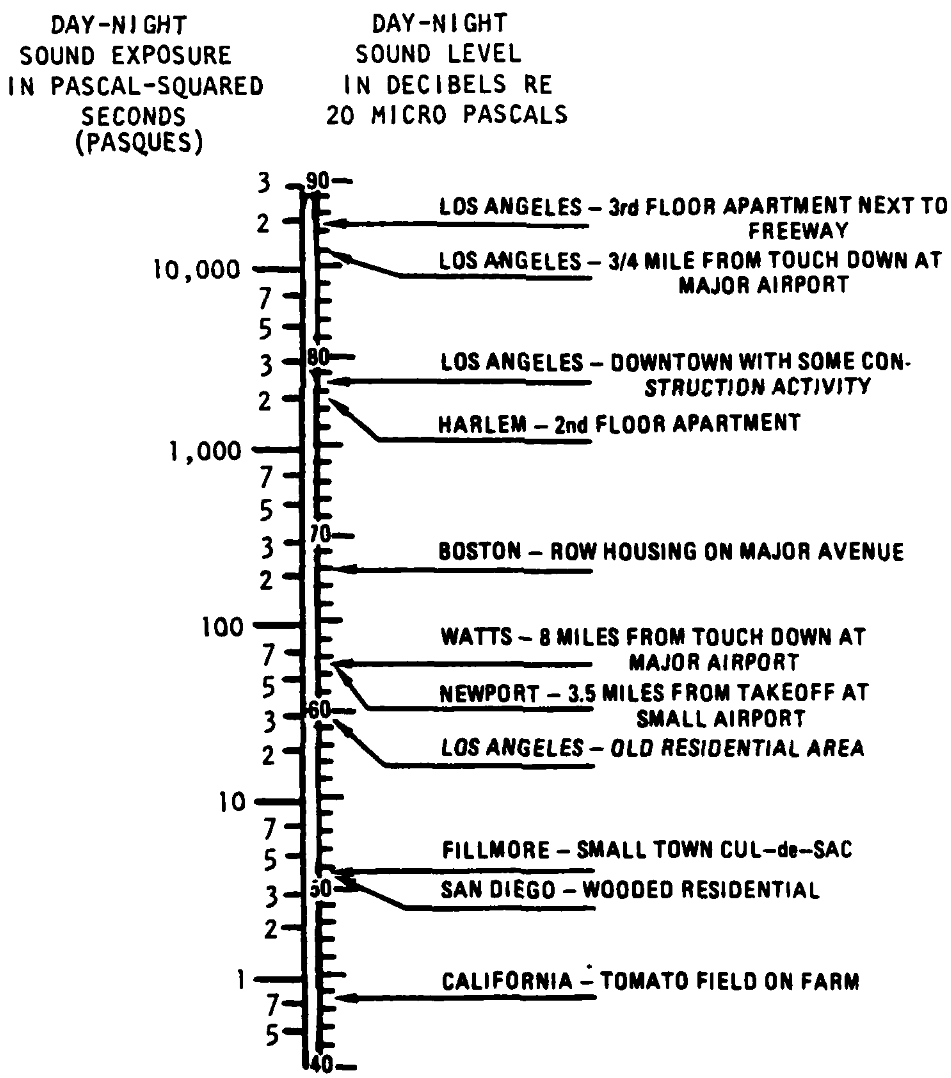

Figure 1. Equivalency of day-night sound exposure and day-night sound level with examples from measured data.

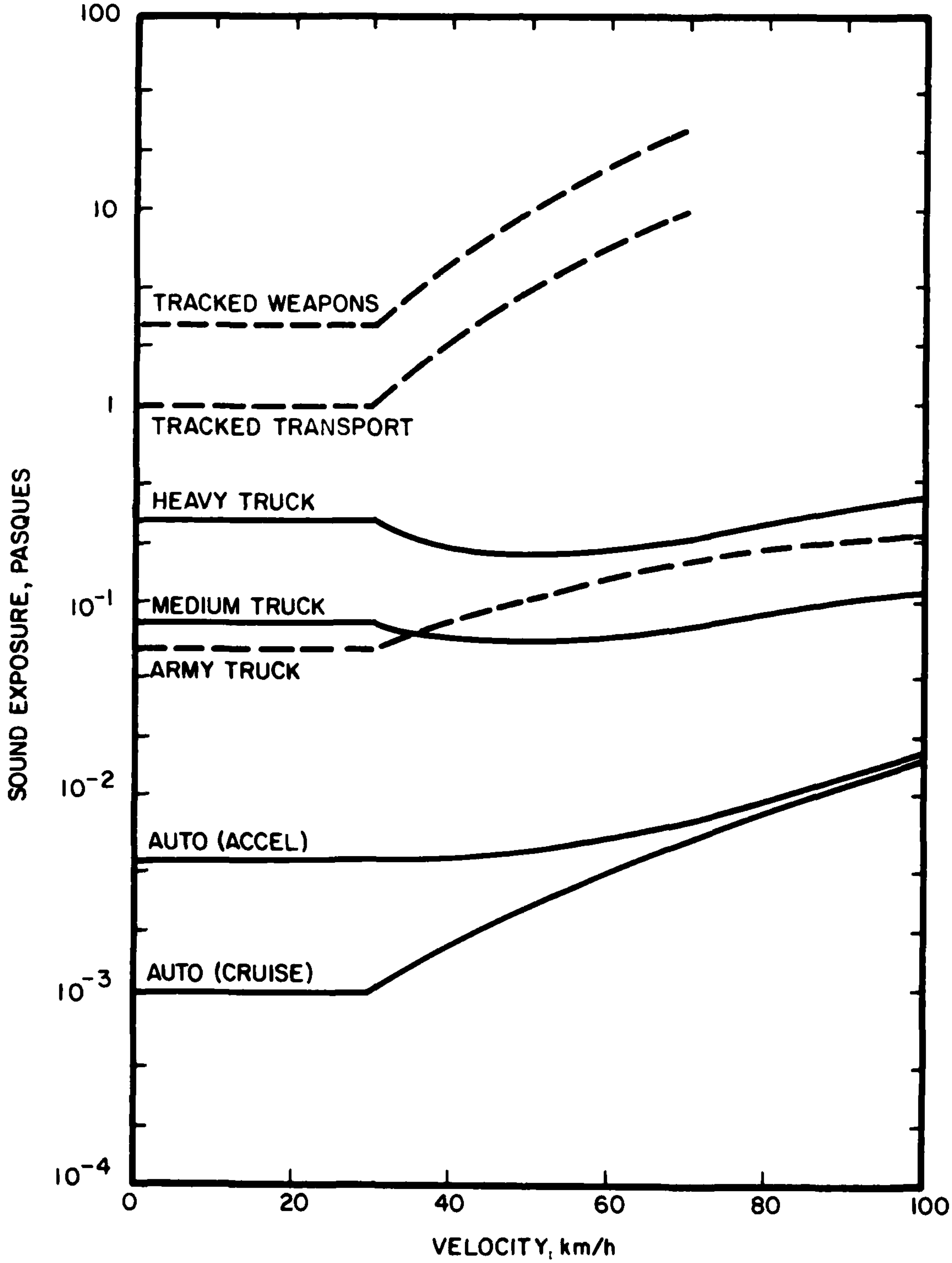

Figure 2. Vehicle single event sound exposure as a function of velocity.

In contrast, the tracked vehicles' noise exposures have a strong velocity relationship. Therefore, they should be calculated at the proper velocity, even in the Initial Screen method, if their numbers are great enough to make their contribution significant to the total noise exposure.

All three methods require the traffic flows by vehicle type to be known for both daytime (0700-2200 hours) and night (2200-0700 hours). However, the data for the Initial Screen method are required for only one direction of traffic. For the Simple Site and Complex Site, ratio tests for directional velocity and flow are used to determine if the two-way flow can be modeled as traveling along a single line that is a geometric mean distance from an observer location (Table 4 has additional details).

All three methods allow modeling of a road gradient; however, there is a stipulation of uniformity for the Initial Screen and Simple Site methods because each uses a single straight segment as model. The gradient noise factor (F) depends on both the amount of gradient and the velocity of the vehicle (Figure 3).[5] For this procedure, its value is 1.0 for uphill gradients of 1 percent or less, at all velocities. Its maximum value is 3.16 at a 7 percent gradient and a velocity of 30 km/h or less. Its maximum value decreases with increasing velocity above 30 km/h and becomes 1.55 at a velocity of 100 km/h. For downhill, the gradient factor is the reciprocal of the uphill value.

Noise Propagation

The vehicle line of travel is assumed to be at the center line of the nearest lane for the Initial Screen method. This leads to a conservative estimate of the day-night sound exposure since it minimizes the distance from the observer location to the source. (Note: no shielding is allowed in this method, so it should always be conservative.) For the other two methods, the traffic flow can be either one or two directions. The distance ratio of far lane to near lane is another test to determine if two directions are required (see Table 4).

All three methods allow use of transmission factors for vegetation, rows of separated houses or other buildings, and ground absorption. To apply these factors to either the Initial Screen or Simple Site method, the vegetation or house row must exist almost continuously in both directions between the road and the observer site. To apply them to a segment in the Complex Site method, they must be continuous within a segment.

To qualify for the transmission factor given in Figure 4a, vegetation must be very dense with underbrush so there is no line of sight from the observer location to the road at all times of the year and vehicles along the segment to which the factor is to be applied. Also, the tree heights should be at least 5 m above the line of sight.[6]

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[5] TM 5-803-2; T. M. Barry and J. A. Reagan; G. S. Anderson, et al., 1976; B. A. Kugler; C. G. Gordon, et al., A Design Guide for Highway Engineers, NCHRP Report 117 (1971).

[6] T. M. Barry and J. A. Reagan; G. S. Anderson, et al., 1976; B. A. Kugler.

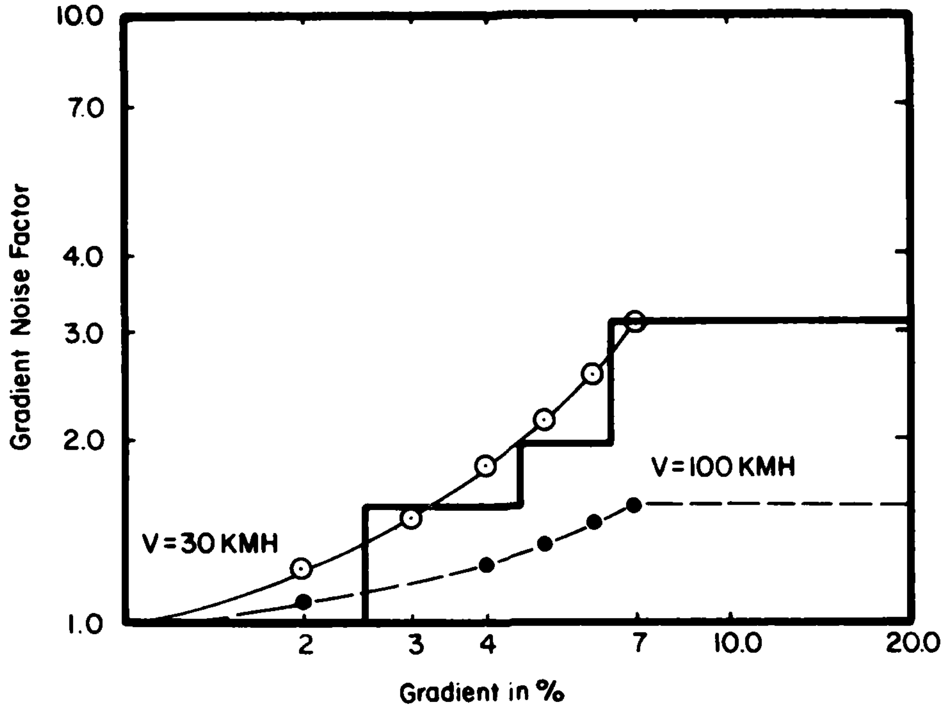


Figure 3. Gradient factor (Fu) for uphill travel and comparison of Equation 9 for two velocities, 30 and 100 km/h, with step function. (From T. M. Barry and J. A. Reagan, FHWA Highway Traffic Prediction Model, FHWA-RD-77-108 [December 1978].)

To qualify for the transmission factor given in Figure 4b, house rows should be nearly parallel to the road, or perpendicular to the line from the observer location to the center of the segments. They also should have relatively uniform spacing.[7]

Ground covered with grass, weeds, and other normal vegetation, freshly plowed ground, and ground covered with snow all absorb sound and phase reversals of the reflected sound waves. This reduces the sound transmitted from a source to an observer location. Paved surfaces and hard-packed smooth earth do not provide ground absorption of sound.

For ground absorption to be effective in reducing the A-frequency-weighted sound from typical vehicles, the sound must be transmitted along a line-of-sight path nearly parallel and close (within 3 m) to the absorption ground surface. When ground absorption is not present, the effect of distance on sound transmission from vehicles moving on a roadway is to reduce the sound exposure in direct proportion to distance. But, when ground absorption is present, less sound is transmitted to the observer location (Figure 5).[8]

[7] T. M. Barry and J. A. Reagan; G. S. Anderson, et al., 1976; B. A. Kugler.
[8] T. M. Barry and J. A. Reagan.

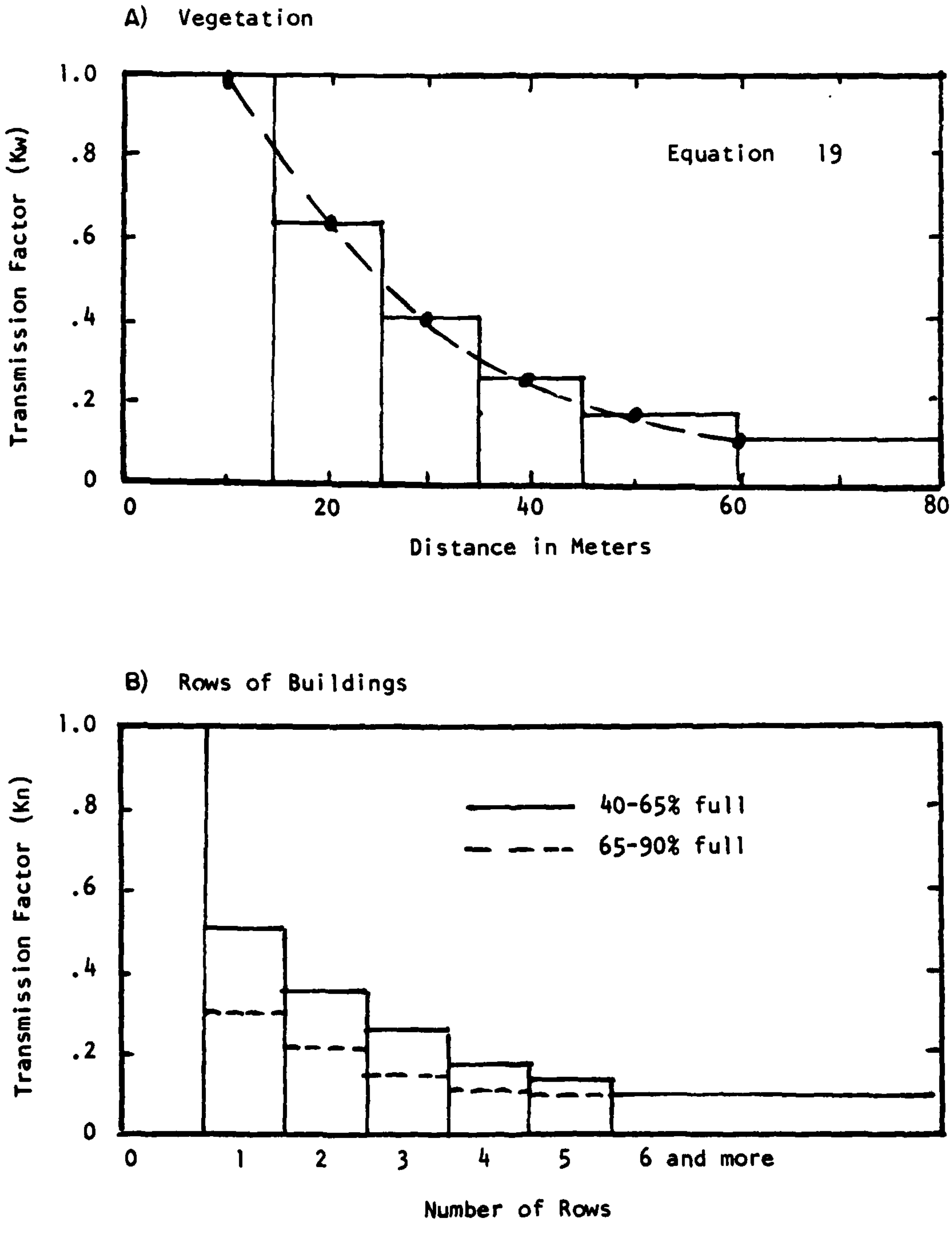


Figure 4. Transmission factors through (a) dense vegetation without line of sight to road vehicles and branches 5 m above line of sight, and (b) nearby uniform rows of buildings or houses.

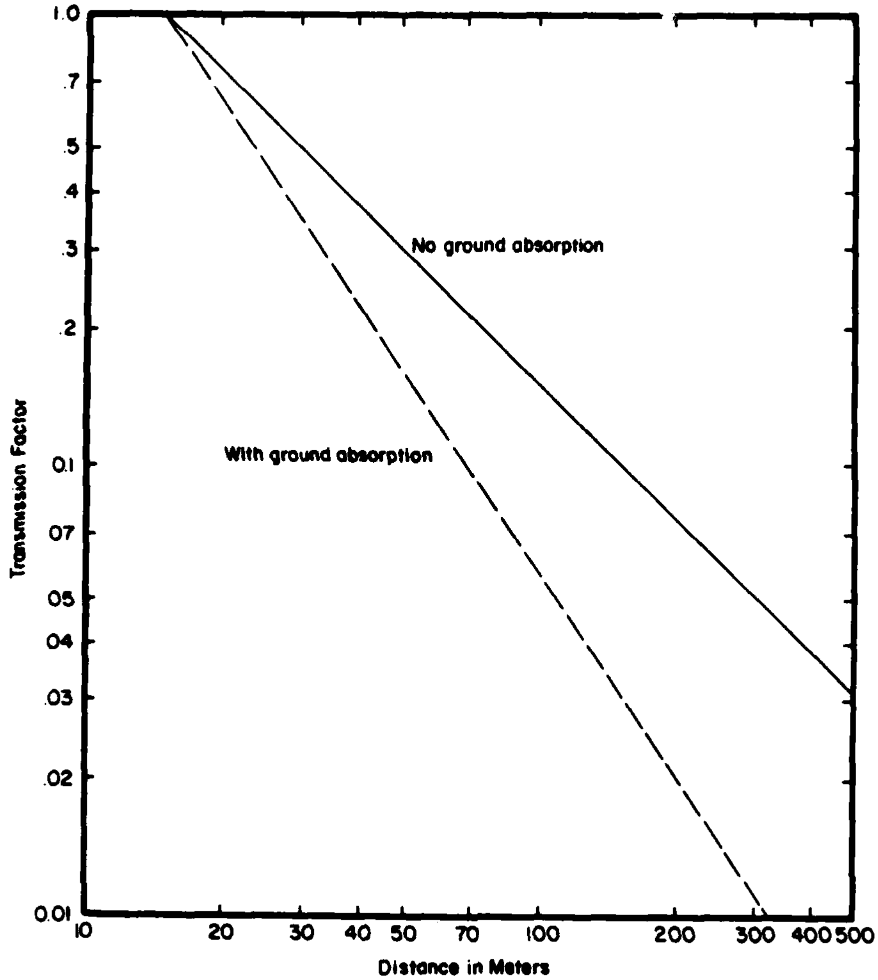


Figure 5. Effect of sound spreading with distance and the additional effect attributed to ground absorption.

Road segments displaced toward the outer limits of the site road models have additional ground absorption because of the great distance from the segment to an observer location. This factor is accounted for in the procedure.

Barrier Design

Walls, earth berms, buildings, natural terrain, and vegetation are commonly used as noise barriers. To varying extents, each reduces noise by partially absorbing it and reflecting it away from receivers. Barriers, which are most effective against high-frequency sounds, must be in the line of sight between the source and the receiver. Barrier effectiveness increases with height, width, and proximity to either the source or the receiver. If the barrier has gaps, the potential benefits of acoustical shielding are substantially reduced. Furthermore, the effects of all barriers are lessened by atmospheric sound scattering and by noise flanking effects around barrier ends.

Besides acoustic advantages, barriers obscure the noise source visually and thus also benefit the noise recipient psychologically. Barriers also tend to keep dust from the highway away from residential areas. The barrier design methodology in this procedure is adapted from another model[9] and produces essentially the same results. It enables direct calculation of the barrier performance factors for an arbitrary segment, rather than using table lookups and interpolation.

A barrier calculated in the Initial Screen method is considered useful only for a preliminary indication of barrier dimensions and siting versus performance. However, the Simple Site method allows optimization of a barrier with finite ends, as long as symmetry is preserved and the ground is nonabsorptive. If either of these conditions is not fulfilled, the barrier calculation must be made with the Complex Site method.

It is usually possible to design a barrier with a performance factor of 0.1. However, it is considerably more difficult to attain 0.03, which usually involves the use of fairly tall structures, high transmission loss, and long length. If the requirement is smaller still, the task becomes more difficult and the design charts incorporate a lower bound of 0.01 for the barrier performance factor.

The effectiveness of a barrier is improved considerably when it is placed close to either the source or to the observer location. The preferred way is to place it close to the source so that all observers benefit alike. However, shoulder design and other safety-related requirements may prohibit barriers closer than 3.3 to 4 m from the edge of the pavement.

Care must be taken in barrier design so the barrier does not tower over the closest house. Esthetics attributes must also be considered carefully. Simple surface texture and landscaping will soften a wall greatly. However, the depth of texture must be much greater on the highway side (if it is to be noticeable to motorists), whereas small-scale texture is adequate for the view from a backyard. Staggered surfaces, in and out, or accordian zigzags in plain view have a little acoustic compromise, but can provide both structural integrity at minimal cost and improved esthetics. (Note: the mean line in such a structure is usually used to ascertain its position for acoustic calculations.) Also, the ends of barrier walls should terminate into earth or some sort of staggered landscaping so they appear to be in harmony with their surroundings.

Earth berms are the most economical barriers, provided that room exists for them.[10] Next higher in cost is masonry, wood, concrete, and steel, in that order. The "transmission loss of the barrier" (transmission of sound through the barrier) depends on the surface mass of the barrier and any sound leaks that may be present. For a barrier performance factor of 0.1, the surface mass should be approximately equal to or exceed 15 to 20 kg/m^2 and openings that contribute to leakage should be less than 1/2 percent. If wood planking is used, it should be tongue and groove to minimize leakage.

[9] T. M. Barry and J. A. Reagan; G. S. Anderson, et al., 1976; B. A. Kugler.
[10] M. Simpson, Noise Barrier Design Handbook, Research Report FHWA-RD-76-58 (FHWA, February 1976).

If the barrier performance factor is 0.03, the surface mass should be equal to or exceed approximately 50 to 60 kg/m^2 and should have negligible leakage. For these and higher performing barriers, concrete or masonry or a heavy composite structure usually provides both the surface mass needed for higher sound transmission loss and the structural strength. Details are available from State Highway Departments, which generally design, construct, and maintain highway barriers, and elsewhere.[11]

[11]M. Simpson.

3 ESTIMATION OF ROADWAY NOISE

This chapter presents a detailed procedure for the estimation of roadway noise. The Initial Screen method is recommended as a starting point for any site with observer locations along a single road.

No barrier is needed and no further calculations are required if either of two conditions are met:

1. If the observer baseline day-night sound exposure (DNSE) estimated by the Initial Screen method is less than one-half the design goal

2. The road is essentially straight and the estimated DNSE is less than the design goal.

If the screening method does not eliminate the requirement for additional noise control, a more detailed analysis should be made using either the Simple or Complex Site method as discussed in Chapter 2.

The procedure is organized to conform to the sequence of lines in the worksheet for Estimation of Roadway Noise and Design (Figure 6). The sequence has 29 steps (the lettered lines in Figure 6) grouped into four functional categories, with each category containing several factors that should be considered in judging the three methods' suitability for any given situation (Table 1). These categories are:

Category	Lines
• Site description and design goal	A-B
• Vehicle noise sources	C-L
• Estimation of baseline noise at observer locations and definition of noise control requirements	M-W
• Design of noise barriers, if required, and comparison with design goals	X-AC

The worksheet has 16 columns with the far right column for totals. The other 15 columns can be used for any combination of vehicle source type, road segment, traffic direction, and observer location. For example, for an initial screening of a situation that had three vehicle types, a single worksheet could be used for five observer locations, each containing three columns--one for each of the three vehicle types. Or, at a complex site with seven vehicle types and a requirement for separate analysis of the noise produced by traffic in two directions, the worksheet could be used for the two directions (near- and far-lane traffic), each containing seven columns--one for each of the seven vehicle types. For this latter situation, a worksheet would be required for each observer location.

ITEM		TOTAL
A) ROAD SEGMENT NO.; LANE IDENTITY		
B) DESIGN GOAL D/N SOUND EXPOSURE (DNSE), PASQUES		
C) VEHICLE TYPES (AA, AC, MT, HT, AT, TT AND TW)		
D) VEHICLE VELOCITY, KMH		
E) SINGLE VEHICLE SOUND EXPOSURE (SE), PASQUES		
F) GRADIENT (Y OR N); VALUE (%); & NOISE FACTORS (Fu+Fd)		
G) AVG. NO. OF VEHICLES IN DAY (0700-2200) (Nd)		
H) AVG. NO. OF VEHICLES AT NIGHT (2200-0700) (Nn)		
I) AVG. EFFECTIVE NO. OF VEHICLES (Nd+10Nn)=Ne		
J) DIRECTIONAL TRAFFIC RATIO, 0.7<R<1.5 (Y OR N?)		
K) DIRECTIONAL VELOCITY RATIO, 0.8<R<1.2 (Y OR N?)		
L) PARTIAL D/N SOUND EXPOSURE AT 15 M, PASQUES		
TOTAL DNSE (PASQUES)		
M) OBSERVER DISTS. TO NEAR & FAR LANES (Df, Dn), M		
N) FAR, NEAR LANE DIST. RATIO, Df/Dn<=2 (Y OR N?)		
O) OBSERVER DIST. (Do), EITHER Df OR Dn, OR De		
P) SEGMENT END ANGLES (ΘL & ΘR), DEG.		
Q) VEGETATION TRANSMISSION FACTOR (Kw)		
R) BUILDING ROW TRANSMISSION FACTOR (Kh)		
S) SHIELDING TRANSMISSION FACTOR (Ks)		
T) BASELINE TRANSMISSION FACTOR (QxRxS) = Kc		
U) GROUND ABSORPTION (a); ANGULAR PROP. FACTOR (Ka)		
V) TRANSMISSION FACTOR (SMALLER OF U & T)x(Do/15)$^{-1}$ = Ko		
W) OBSERVER BASELINE DNSE(L), PASQUES		
TOTAL DNSE (PASQUES)		
X) BARRIER DIST. TO SOURCE (Db), M		
Y) BREAK DIST. IN LINE OF SIGHT (B), M		
Z) BARRIER END ANGLES (ØL & ØR), DEG.		
AA) PATH LENGTH DIFFERENCE (Po), M; FRESNEL NO. (No)		
AB) BARRIER TRANSMISSION FACTOR (Fb)x(Do/15)-1		
AC) OBSERVER DNSE(L) WITH BARRIER, PASQUES		
TOTAL DNSE (PASQUES)		

Figure 6. Worksheet for estimation of roadway noise and barrier design.

Table 1

Summary of Factors Considered in the Three Methods

Factor	Method: Initial Screen	Method: Simple Site	Method: Complex Site
Site description, design goal			
Typical no. of observers	1 to 3	1 to 3	As required
Road geometry	Single straight approximation	Single straight approximation	Straight segments approximate curves and gradients
Length road section beyond any observer	Infinite	10 times observer distance	5 to 10 times observer distance, depends on shielding
Intersecting roads	None	None	Allowed
Significant barrier in median	Ignored	Considered	Considered
Direction of traffic	1	1 or 2	1 or 2
Vehicle noise sources			
No. of types	1 to 7	1 to 7	1 to 7
Maximum velocity (km/h)	70	100	100
Annual average number of vehicles by types in day and at night	Yes	Yes	Yes
Noise varies with velocity	No	Yes	Yes
Gradient is allowed	Yes, if uniform	Yes, if uniform	Yes
Test of directional velocity ratio	No	Yes	Yes
Test of directional traffic flow ratio	No	Yes	Yes

Table 1 (Cont'd)

Factor	Method: Initial Screen	Simple Site	Complex Site
Partial day-night sound exposure by type (at 15 m)	Yes	Yes	Yes
Noise propagation			
Observer-source distance perpendicular to road	To center of nearest lane	To 1 or 2 lanes, depends on tests	To 1 or 2 lanes per segment, depends on tests
Test of far lane, near lane distance ratio	No	Yes	Yes
Angular range	Nominal 85° symmetrical	Nominal 85° symmetrical	Defined by segment
Dense vegetation, woods	Continuous	Continuous	Variable
Row(s) of houses	Continuous	Continuous	Variable
Shielding (topography)	Flat	Uniform symmetrical variation	Variable
Ground absorption	Uniform distribution	Uniform distribution	Variable
Test of sound observer heights for absorption	Yes	Yes	Yes
Observer baseline DNSE	Yes	Yes	Yes
Noise Barrier Design			
Angular range	Nominal 85° symmetrical continuous single ht.	Continuous symmetrical single ht. variable end angle	Variable hts and end angles
Propagation around barrier ends	None considered	Defined symmetrical end segments	Arbitrary defined segments
Observer DNSE with barrier	Only preliminary approximation	Yes	Yes

Site Description and Design

Step A: Road Segment Numbering and Lane Identity

Identify for possible analysis the nearest observer locations along the roadway, together with other sites for which analysis is desired. Use the Initial Screen method to determine the most distant observer locations of probable interest.

Initial Screen. Model the roadway by a single straight segment of the infinite length with all traffic flow along the center line of the near lane.

Simple Site. Model the roadway by a single straight segment of infinite length with the two opposite traffic flows treated independently, unless tests show they can be combined.

Complex Site. Model the roadway by a connected series of straight line road segments selected to approximate actual road geometry and to provide substantially uniform conditions of traffic flow, gradient, vegetation, house rows, and shielding along each segment. The two opposite traffic flows are treated independently on each segment unless tests show they can be combined. For additional detail, see Steps N through P below and for a summary of requirements for segments see Table 4.

Step B: Design Goal Day-Night Sound Exposure

Establish a design goal that fits the project using the most recent relevant directive or Chapter 4 of TM 5-803-2, reference 3-1. The recommended noise level for design will probably be stated in terms of the A-frequency-weighted DNL in decibels (dB). It should be restated in terms of the linear DNSE scale. The unit of sound exposure is pascal-squared-seconds, which is abbreviated as pasques.

A DNSE of 10 pasques is about 55 dB on the DNL scale; 100 pasques is about 65 dB and 1000 pasques is about 75 dB. A DNSE of 30 pasques is about 60 dB and 300 pasques is about 70 dB on the DNL scale. For an exact transformation of DNL to DNSE, use Equation 1.

$$\text{DNSE (DG)} = 10^{(\text{DNL} - 44.614)/10} \text{ pasques} \qquad \text{[Eq 1]}$$

Where DNSE(DG) is the design goal day-night sound exposure.

Vehicle Noise Sounds

Step C: Vehicle Types

Identify the types of vehicles using each road segment under consideration in terms of the following seven categories.

- Automobile accelerating from stop (AA)
- Automobile at constant cruise speed (AC)
- Commercial medium truck (MT)
- Commercial heavy truck (HT)
- Army truck (AT)
- Tracked transport carrier (TT)
- Tracked weapons carrier (TW)

It is unlikely all seven vehicle types would be required for the analysis at a single site; three is a more typical value. It is also possible to delete from further analysis types for which the contribution to DNSE is very small (i.e., partial DNSE in step L is less than 1 percent of the total DNSE at 15 m).

Step D: Vehicle Velocity

Determine the average vehicle velocity in kilometers per hour for each type of vehicle in Step C for each road segment and each direction.

Step E: Single Vehicle Sound Exposure

Obtain the single vehicle sound exposure (SE) in pasques for each type of vehicle in Step C for the corresponding velocity from Step D in accordance with the method, as follows:

Initial Screen. If the vehicle velocities exceed 70 km/h or if the noise from tracked vehicles is significant, use the Simple and Complex Site methods to determine the SE as described below. Otherwise, use the comstant values for sound exposure given in Table 2.

Simple and Complex Sites. Use Equations 2 through 8 to obtain the single vehicle sound exposure values at a distance of 15 m from the vehicle center line.

Vehicle Type	0 to 30 km/h	30 to 100 km/h	
AA	$SE(15,AA) = 4.6\times10^{-3}$	$= 5.60\times10^{-7}(194{,}984 + V^{3.175})/V$	[Eq 2]
AC	$SE(15,AC) = 9.1\times10^{-4}$	$= 5.59\times10^{-7}\ V^{2.175}$	[Eq 3]
MT	$SE(15,MT) = 7.8\times10^{-2}$	$= 1.43\times10^{-6}(1{,}523{,}048 + V^{3.4})/V$	[Eq 4]
HT	$SE(15,HT) = 2.4\times10^{-1}$	$= 3.99\times10^{-6}(1{,}714{,}982 + V^{3.4})/V$	[Eq 5]
AT	$SE(15,AT) = 5.8\times10^{-2}$	$= 1.59\times10^{-3}\ V^{1.06}$	[Eq 6]
TT	$SE(15,TT) = 1.0$	$= 1.13\times10^{-4}\ V^{2.68}$	[Eq 7]
TW	$SE(15,TW) = 2.5$	$= 1.83\times10^{-4}\ V^{2.8}$	[Eq 8]

Table 2

Constant Values of Single Vehicle Sound Exposure Velocities Under 70 km/h for Use in Initial Screen

Vehicle Type*	Single Vehicle Sound Exposure (pasques)
AA	5.0×10^{-3}
AT	2.5×10^{-3}
MT	6.3×10^{-2}
HT	0.2
AT	0.1
TT	4.0
TW	10.0

*Symbols are defined in text.

Step F: Gradient Noise Factor

The gradient noise factor is used to account for the increase in single vehicle sound exposure for uphill travel, and the decrease for downhill travel. For uphill, the fraction varies between a minimum of 1.0 and a maximum of 3.16; for downhill, it varies between a maximum of 1.0 and a minimum of 0.316. If there is no gradient, enter N on the worksheet.

Initial Screen. Use a value of 1.58 (one-half the maximum uphill value) as a multiplier of the sound exposure. Alternatively, use Equation 9a to calculate the correct value of the noise factor for uphill (Fu), divide it by 2.0, and use the result as a multiplier of the single-vehicle sound exposure.

Simple and Complex Sites. The gradient noise factors, Fu and Fd for uphill and downhill, respectively, are calculated from the following:

For uphill,

$$
\begin{aligned}
&0<G<1, \ Fu = 1.0 \\
&1\leq G<7, \ Fu = 0.83 \times 10^{0.083G} \times (V/30)^{(1-G)/10} \\
&G\geq 7, \ Fu = 3.16 \times (V/30)^{(1-G)/10}
\end{aligned}
\qquad [\text{Eq 9a}]
$$

For downhill,

$$0 \le G < 1, \quad Fd = 1.0$$

$$1 < G \le 7, \quad Fd = 1.2 \times 10^{0.083G} \times (V/30)^{(G-1)/10} \qquad \text{[Eq 9b]}$$

$$G > 7, \quad Fd = 0.316 \times (V/30)^{(G-1)/10}$$

Apply these factors as multipliers to the single-vehicle sound exposure values to obtain corrected values for both uphill and downhill directions.

For modeling the actual gradient with a set of constant gradient road segments, it is usually adequate to consider only the four gradient ranges given in Table 3. The gradient used in Equations 9a and 9b is then the average gradient of each segment.

Steps G, H, and I: Traffic Flow

Define the number of vehicles for each road segment and each vehicle type during an annual average day (Nd) (0700-2200 hours) and night (Nn) (2200-0700 hours). Calculate the effective number of vehicles (Ne) (to be used in calculating the DNSE) by:

$$Ne = Nd + 10Nn \qquad \text{[Eq 10]}$$

Initial Screen. Combine the traffic flows in both directions for each vehicle type so that Nd, Nn, and Ne represent the total annual average daily values for the road segment.

Simple Site. Calculate the traffic flows using Equation 10 in each direction separately so each direction of traffic can be modeled separately if later tests show such modeling is required.

Complex Site. Calculate the traffic flows on each segment using the above method for a simple site.

Step J: Directional Traffic Ratios

Initial Screen. Skip to Step L.

Simple Site. Calculate the ratios (Rd) of the annual average daily traffic flows in each direction for each vehicle type using the following equation:

$$Rd(TYPE) = Ne(TYPE, DIR\ 1)/Ne(TYPE, DIR\ 2) \qquad \text{[Eq 11]}$$

If the ratio (Rd[TYPE]) for any type of vehicle is greater than 1.5 or less than 0.7, the traffic flows in the two directions should be modeled separately.

Complex Site. Calculate the ratios for each segment using the above method for a simple site.

Table 3

Suggested Gradient Subdivision Categories for Determining Road Segments

Gradient Range (%)	Gradient Model Calculation
$0 \leq G \leq 1$	Do not model, gradient noise factor is 1
$1 < G \leq$	Model and calculate using average gradient of real road in each range
$3 < G \leq 5$	
$G < 5$	

Step K: Directional Velocity Ratio

Initial Screen. Skip to Step L.

Simple and Complex Site. Calculate the ratios (R) of the average velocities in each direction for each type of Army vehicle and for automobiles using the following equation:

$$R(TYPE) = V(TYPE, DIR\ 1)/V(TYPE, DIR\ 2) \qquad [Eq\ 12]$$

If the ratio (R[TYPE]) for any type of Army vehicle or automobile is greater than 1.2 or less than 0.8, traffic flows in each direction should be modeled separately. However, if any traffic type comprises only a small part of the noise (i.e., less than 10 percent of the partial DNSE at 15 m), the ratios for automobiles may exceed these limits without requiring separate analyses in each direction.

Step L: Partial Day-Night Sound Exposure at 15 M

Calculate the partial day-night sound exposure (PDNSE) at the reference distance of 15 m in each vehicle type column, accounting for the gradient factor (Fu or Fd) as appropriate, using the following equation:

$$PDNSE(15,TYPE) = Ne(TYPE) \times SE(15,TYPE) \qquad [Eq\ 13]$$

Then, for each road segment and lane, compute the total DNSE at 15 m from the vehicle center line by summing the PDNSE values for all the types. Use the following equation:

$$DNSE(15) = \sum_{\text{ALL TYPES}} PDNSE(15,TYPE) \qquad [Eq\ 14]$$

The DNSE(15) data can be used both to screen out unnecessary further work and to identify locations that may be critical and thus require additional effort in defining segments.

If it is desired to convert the DNSE to DNL, the following equation can be used:

$$DNL(15) = 44.614 + 10 \log DNSE \text{ (dB)} \qquad \text{[Eq 15]}$$

Noise Propagation to Observer

Steps N, M, O, and P: Observer Distances

Initial Screen (Figure 7). Determine the distance (Dn) from the observer site to the center line of the nearest lane of the roadway segment to be analyzed. This distance is measured along a line perpendicular to the center line of the lane. Define the observer distance (Do) as equaling the distance to the nearest lane and record this value in line O of the worksheet in Figure 6.

Simple Site (Figure 8). Determine the distances from selected observer sites (Dn) to the near lane and the distances (Df) to the far lane. Check the results of Steps F, J, and K to see if there is already a requirement to model the traffic flows in two separate directions. If there is a gradient over 1 percent in Step F or if one of the ratios in either of Steps J and K exceeds the suggested bounds, the traffic should be modeled in two separate directions. Moreover, if the road is a divided highway and its median exceeds 60 m wide, if the elevation of opposing traffic differs by more than 1.5 m and line of sight exists, or if the road has a median barrier with a barrier performance factor to the nearest observer of 0.3 or less, the traffic should be modeled separately in two directions. The lines of travel for the two directions should be the center lines of the near and far lanes unless the roadway use patterns suggest selection of a more appropriate travel line.

If there is no requirement for modeling in both directions from the results of Steps F, J, and K, then calculate the ratio of the distances to the far and near lanes:

$$Rdfn = Df/Dn \qquad \text{[Eq 16]}$$

If Rdfn is more than 2, both directions of traffic should be modeled separately using the center line of the near and far lanes as the lines of travel for the two directions.

If Rdfn is less than 2 and the other conditions above have been met, the traffic in both directions can be combined into one analysis. The combined traffic should be modeled as if it were traveling on a line located at the effective distance from the nearest observers. The effective distance (De) is the geometric mean of Df and Dn and is calculated by:

$$De = \sqrt{Df \times Dn} \qquad \text{[Eq 17]}$$

Define the observer distance (Do) as equaling the effective distance and record its value in Line O (Figure 6). Continue to Step Q.

Complex Site (Figure 9 and Table 4). There are five substeps in analyzing the complex site.

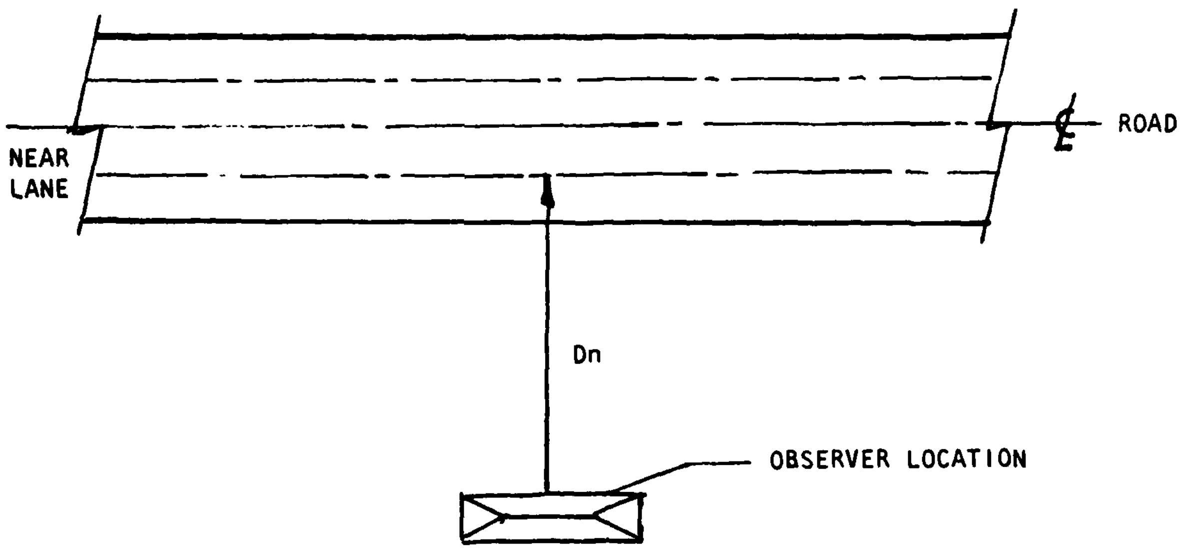


Figure 7. Initial Screen geometry.

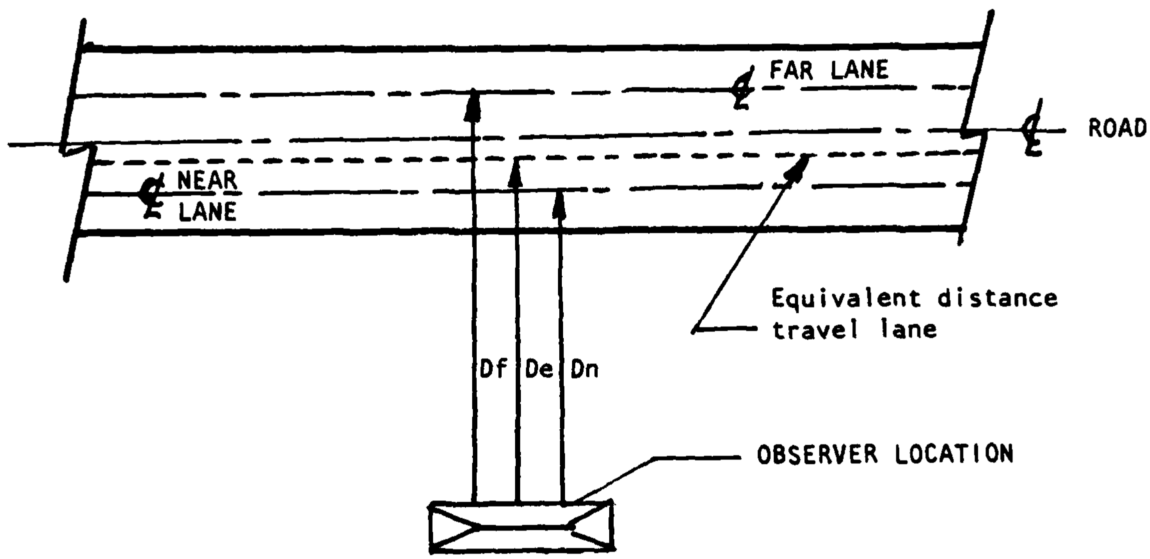


Figure 8. Simple Site geometry.

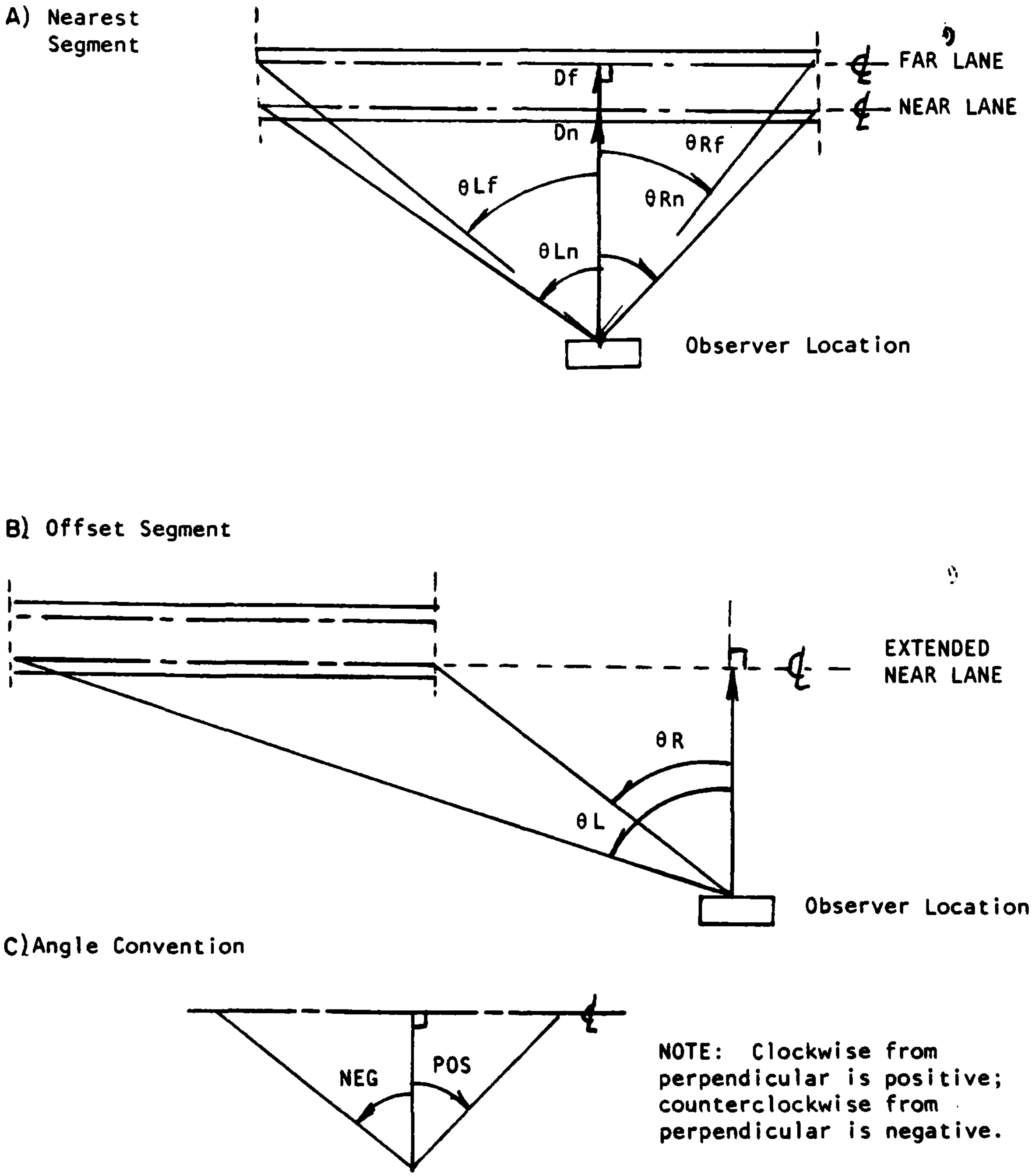


Figure 9. Basic segment elements for Complex Site.

Table 4

Summary of Complex Site Requirements for Segments

Factor	Criterion
1. Length of study area	• For flat terrain without shielding, 5 times the observer location distance for any observer. • If shielding exists between the observer and the road, up to 10 times the observer distance from any observer, as long as line of sight exists.
2. Gradient	• Single segment in each of the three gradient categories: 1-3%, 3-5%, >5%.
3. Curves	• One or more pairs of straight line segments of length equal to the length of the curved road center line. • Ratio of the observer distance to the modeled travel lane (near, far, or equivalent) divided by the similar observer distance to the real road should be between 0.7 and 1.5.
4. Shielding, vegetation, structure and ground absorption	• If any of these factors have a significant noise control effect on results for critical observer locations, define segments within which the factor is substantially uniform.
5. Road intersections	• Subdivide the road into segments if any of the ratios of traffic flow rates for any type of vehicle on the two sides of the intersection exceed the range of 0.7 to 1.5, or if the ratio of average speeds exceeds the range of 0.8 to 1.2. • Include segment (s) to model the intersecting road if its noise is of possible significance to observer locations in the study area.
6. Varying requirements to subdivide opposing traffic may lead to additional segments	• Center median width > 60 m • Median barrier transmission factor < 0.3 • Difference in elevation of opposing traffic > 1.5 m • Directional traffic volume ratio for any vehicle type outside range of 0.7 to 1.5 • Directional velocity ratio for any vehicle type outside range of 0.8 to 1.2

1. The basic element in modeling a complex site is a straight road segment that approximates some part of the real road. The greatest detail is required in modeling the road near or adjacent to observer locations. Less detail is required for estimating the noise contributions from segments which have observer angles over $\pm 60^{o}$.

2. Each segment and traffic flow lane is identified by an observer distance and the segment end angles (θ L and θ R), as shown in Figure 9. The observer distance is determined for each segment using the same procedure described for the simple site. The distance is measured along a perpendicular from the observer location to the segment travel lane or its extension. The segment end angles are measured from the perpendicular to the left (θ L) and right (θ R) ends of the segment. Angles measured clockwise from the perpendicular are positive, whereas counterclockwise values are negative.

3. The number and location of segments required for modeling a road and its associated observer locations depend on the site parameters--especially the amount of noise with respect to the design goal. Table 4 summarizes the various aspects of segment requirements.

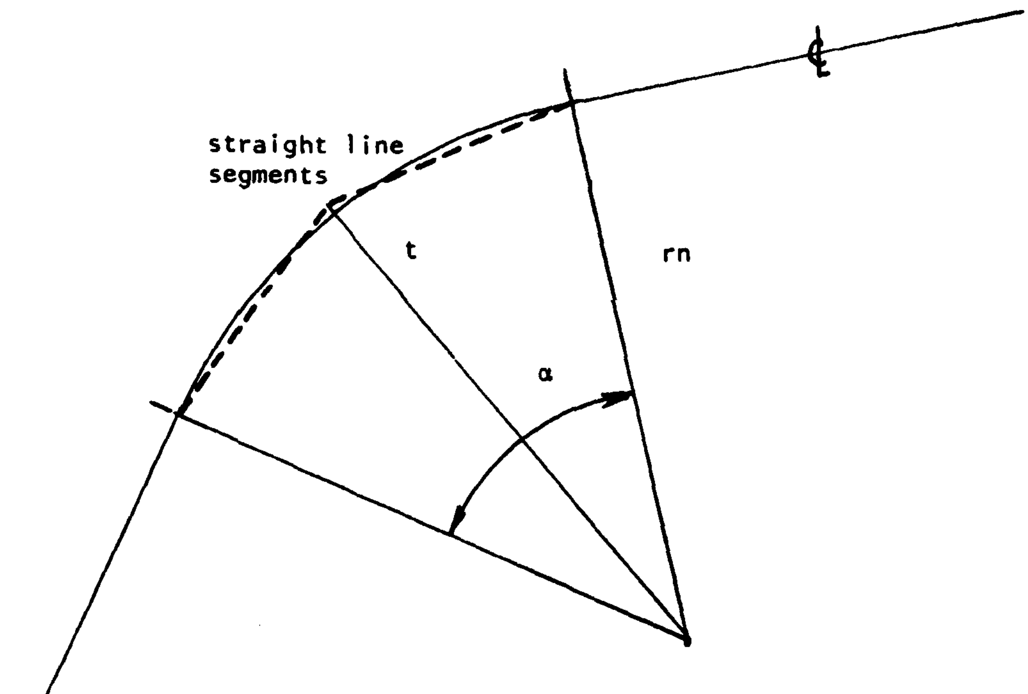
4. To model curves use an even number of straight segments selected so their length equals that of the actual road center line. First, locate the approximate center of curvature and define the approximate angle of the curve. Second, choose an even number of segments. If the total angle is 60^{o} or less, the substitution of two straight segments (each representing 30^{o} or less) for the curve will result in a maximum lateral error of 2 percent. If the total angle is 90^{o} or less, the substitution of two segments results in a maximum lateral error of 5 percent, and if it is 120^{o}, a maximum lateral error of 9 percent results.

Calculate the segment locations using Equation 18 on Figure 10. Then, examine the trial choice of straight segments on the map with respect to the most critical observer locations. The maximum error occurs at the bisector between each pair of straight line segments. The error in other locations is less, averaging close to zero, with part of the segment inside the curve and part outside the curve. The ratios of the observer distances to the segment and to the true road should not be more than 1.5 or less than 0.7, with the observer location on the same side of both the straight segment model and the true road.

5. For each observer location to be analyzed, identify the segments required and revise the worksheet layout as appropriate. Then compute lines M, N, O, and P of the worksheet (Figure 6) as necessary to continue.

Step Q: Vegetation Transmission Factor

The vegetation transmission factor (Kw) applies to sound transmitted through dense woods with underbrush. The factor should only be computed for segments in which:



$$t = r\left(\cos\frac{\alpha}{n}\right) + \sqrt{\left(\frac{\alpha}{57.3n}\right)^2 - \sin^2\frac{\alpha}{n}} \qquad \text{[Eq 18]}$$

where t = distance along segment pair bisector to segment end

r = road center line radius of curvature

α = total angle of curve in degrees

n = the number of segments used (2, 4, 6 ....)

Figure 10. Approximation of curve with a pair of straight line segments whose length equals the arc length.

- Vegetation is fairly uniform across the segment.

- Vegetation blocks the line of sight of the road segment from the observer location.

- The height of the trees is at least 5 m above the direct line of sight from the observer location to the roadway segment.

If these conditions exist and the distance through the woods (Dw) perpendicular to the roadway exceeds 15 m, compute the vegetation transmission factor (Kw) from:

$$Kw = 10^{-.02(Dw-10)} \text{ for } 15 < Dw < 60 \text{ m}$$
$$= 0.1 \text{ for } Dw \geq 60 \text{ m} \qquad \text{[Eq 19]}$$
$$= 1.0 \text{ for } Dw \leq 15 \text{ m}$$

Several values of Kw are shown for various distances in Table 5.

Step R: Building Row Transmission Factor

The building row transmission factor (Kh) applies to sound transmitted through one or more rows of houses or other buildings. For this factor to apply, the structures are assumed to be essentially continuous along a segment, with a single row blocking the view from the observer location to at least 40 percent of the length of the roadway segment. Values of the building row transmission factor are given in Table 6.

Step S: Shielding Transmission Factor

The shielding transmission factor (Ks) is calculated using the same method as for calculating a barrier transmission factor in Steps X through AB in Chapter 4. If shielding is the result of natural terrain that has sound absorbing ground cover on its roadway side, reduce the transmission factor by two, so that it becomes one-half the value calculated by the barrier method. (Note: this adjustment for ground absorption is the same as that applied to earth berms used as a barrier or as part of a barrier.)

Initial Screen. Topography is assumed to be flat without shielding. Therefore, Ks = 1.0.

Simple Site. Shielding is allowed if it is of near uniform height relative to the roadway. The shielding may extend for only part of distance along the straight model of the roadway if it is symmetrical with respect to the perpendicular line from the observer site to the roadway. If it is not symmetrical and is believed to be significant, the Complex Site method should be used.

Complex Site. Shielding is allowed if it is of near uniform height relative to the roadway across any segment. When shielding is present, the segments are usually defined to fulfill this condition.

Table 5

Vegetation Transmission Factor for Dense Woods Without Line of Sight Between Road Segment and Observer Locations, With Tree Heights at Least 5 Meters Above the Line of Sight

Distance Range (m)	Vegetation Transmission Factor
0-15	1.00
15-25	0.63
25-35	0.40
35-45	0.25
45-60	0.16
>60	0.10

Table 6

Building Row Transmission Factor (Kh) for Buildings About Uniformly Placed Across the View of a Road Segment From the Observer

Number of Rows	Blockage of View	
	40-65%	65-90%
1	0.50	0.30
2	0.35	0.22
3	0.25	0.16
4	0.18	0.11
5	0.13	0.10
6 and above	0.10	0.10

Step T: Combined Transmission and Angular Propagation Factors

The combined transmission factor (Kc) is determined by multiplying the results of Steps Q, R, and S together. However, the value obtained by multiplying the transmission factors for vegetation and building row factors, Kw x Kh, cannot be less than 0.1. Therefore, the combined transmission factor (Kc) is given by:

$$Kc = Kw \times Kh \times Ks \qquad \text{[Eq 20a]}$$

for $0.1 < Kw \times Kh < 1.0$. Or,

$$Kc = 0.1\ Ks \qquad \text{[Eq 20b]}$$

For $Kw \times Kh < 0.1$. (Note: for the Initial Screen method, Ks = 1.0.)

Complex Site. The combined transmission factor (Kc[s]) for a segment in a complex site is calculated by multiplying the combined transmission factor corresponding to a segment Kc by the proportion of 180° represented by the segment. Kc is calculated from Equation 20 using each factor relevant to the segment. Thus,

$$Kc(s) = Kc \times (\theta R - \theta L)/180 \qquad \text{[Eq 21]}$$

If the observer location is very close to, or even on, the segment's extended line of travel with a value of Do less than 15 m, the combined transmission factor should be calculated from:

$$Kc(s) = 4.77x(Kc)x(Do/15)x(1/Dsn - 1/Dsf) \qquad \text{[Eq 22]}$$

where Dsn is the distance from the observer location to the nearest end of the segment and Dsf is the distance to the farthest end of the segment. (Note: 1/Dsf may be zero if the segment extends a great distance.)

Step U: Ground Absorption and Angular Propagation Factors

If more than one-half the ground between the observer site and the nearest roadway travel lane (i.e., more than 1/2 of Dn or De) is paved, hard-packed dirt, or otherwise nonabsorptive, the ground should be considered nonabsorptive; thus, the ground absorption factor (Ka) = 1.0. If the Complex Site method is used, proceed to the Complex Site paragraph in this step. If either the Initial Screen or Simple Site method is used, proceed to Step V.

If more than one-half the ground is covered with grass, weeds, or other vegetation, or is freshly plowed or covered with snow, the ground surface can be considered absorptive.

For $Do \geq 15$ m and the average height of the line of sight between source and observer location ≤ 3 m, the ground absorption factor (Ka) is:

$$Ka = \sqrt{15/Do} \qquad \text{[Eq 23a]}$$

If Do is less than 15 m,

$$Ka = 1.0. \qquad \text{[Eq 23b]}$$

If the average height of the line of sight (Ha) exceeds 3 m and Do$\geq$15 m,

$$Ka = (15/Do)^{.5(3/Ha)^2} \qquad \text{[Eq 23c]}$$

Initial Screen. If the ground surface is absorptive and the average height is less than 3 m, nearly uniform through an angle of 160^o ($\pm$80^o from a perpendicular line from the observer site to the road), calculate $\overline{Ka}$ from Equation 23a. If Do is less than 15 m, use Equation 23b.

Simple Site. Use the same method as described above for the Initial Screen.

Complex Site. If the ground surface is absorptive and nearly uniform between the angles $\theta R(s)$ and $\theta L(s)$ associated with the ends of segment (s), and if the average height of the line of sight is less than 3 m, the ground absorptive factor can be estimated from:

$$Ka = [\sqrt{15/Do}) \times (\theta R-\theta L)/200 \qquad \text{[Eq 24]}$$

For segments with end angles $|\theta R|$ or $|\theta L| \leq 60^o$, the quantity $(\theta R-\theta L)/200$ approximates the angular propagation factor. Also, if one end angle is 90^o and the other $|\theta| < 60^o$, then the quantity $(78 - |\theta|)/200$ can be used to approximate the angular propagation factor.

To calculate Ka with greater accuracy, or for segments with one or more end angles in the range for which Equation 24 is invalid, use the angular propagation factor for ground absorption ($A[\theta R, \theta L]$) in the following:

$$Ka = [\sqrt{15/Do})] \times A(\theta R, \theta L) \qquad \text{[Eq 25a]}$$

where $A(\theta R,\theta L) = A(|\theta R| - A(|\theta L|)$ when θR and θL have the same sign, or $A(\theta R,\theta L) = A(|\theta R|) + A(|\theta L|)$ when θR and θL have different signs, and $A(|\theta|)$ is:

$$A(|\theta|) = (5.32\text{x}10^{-3} + 1.047\text{x}10^{-5}\ |\theta| - 2.503\text{x}10^{-7}\ |\theta|^2) \times |\theta|$$

If Do is less than 15 m, Dsn is less than 30 m, and Ha is less than or equal to 3 m:

$$Ka = A(\theta R,\theta L) \qquad \text{[Eq 25b]}$$

If the average height of the line of sight (Ha) exceeds 3 m and Do equals or exceeds 15 m:

$$Ka = (15/Do)^{+.5(3/Ha)^2} \times A\ (\theta R,\theta L) \qquad \text{[Eq 25c]}$$

If the observer location is very close or even on the segment's extended line of travel, and Do is less than 15 m, the ground absorptive factor can be calculated from:

$$Ka = .212x(Do/15)x\{(15/Dsn)^{1.5}-(15/Dsf)^{1.5}\} \qquad \text{[Eq 25d]}$$

Step V: Transmission Factor for Baseline Estimate to an Observer Site

The transmission factor (Ko) to be used in the baseline estimate should be the smaller of the transmission factors found in Steps T and U, Kc and Ka, respectively, times the distance ratio to account for the spreading of sound.

If Ka is less than Kc, the transmission factor to the observer is given by:

$$Ko = Ka(15/Do) \qquad \text{[Eq 26a]}$$

If Kc is less than Ka:

$$Ko = Kc\ (15/Do) \qquad \text{[Eq 26b]}$$

Step W: Observer Baseline Day-Night Sound Exposure

The observer site baseline DNSE(L)* can be calculated directly from the DNSE(15) if no shielding is present that varies with vehicle type. If no shielding is present, calculate the observer DNSE(L) from:

$$DNSE(L) = Ko \times DNSE(15) \qquad \text{[Eq 27]}$$

If shielding is present, calculate the partial observer DNSE(L,TYPE), and then sum the partial values to obtain the observer DNSE(L). Thus,

$$PDNSE(L,TYPE) = Ko(TYPE) \times PDNSE(15,TYPE) \qquad \text{[Eq 28]}$$

and,

$$DNSE(L) = \sum_{\text{ALL TYPES}} PDNSE(L,TYPE) \qquad \text{[Eq 29]}$$

Initial Screen. Since no shielding is allowed, use Equation 27.

Simple Site. Use either Equation 27 or Equations 28 and 29, depending on the presence or absence of shielding.

Complex Site. For each segment, calculate the observer DNSE(L,s) from each segment (s). Use either Equation 27 or Equations 28 and 29, depending on the presence or absence of shielding in the observer transmission factor. Then, compute the observer site DNSE(L) from the sum of the values of observer

*L is the alphanumeric used to designate each observation site.

DNSE(L,s) from each segment analyzed that makes a significant contribution to the total. Thus,

$$DNSE(L) = \sum_{\text{ALL SEGMENTS}} PDNSE(L,s) \qquad \text{[Eq 30]}$$

Comparison With Design Goal. Compare the observer baseline DNSE(L) with the design goal DNSE(DG) from line B of Figure 6. If the ratio of DNSE(L)/DNSE(DG) is less than 1.0 (0.5 for the Initial Screen), no barrier is required. If this condition is not met, a barrier may be required and a more detailed analysis is warranted.

4 NOISE BARRIER DESIGN

Preliminary Design Procedure

To start the barrier design process, first determine the required barrier performance, its related Fresnel number, and its relationship to the basic design distance between source and barrier (Db) and the break distance (B). These preliminary relationships are useful in developing practical barrier siting and height alternatives. The performance of each alternative is calculated and compared to the requirements. If the performance for an alternative is not good enough, its barrier height should be increased (or its distance from the road changed) until its performance is satisfactory.

This procedure for the development and evaluation of alternative designs contains the following preliminary design substeps, in addition to detailed Steps X through AC, for calculating barrier performance.

1. Determine the required noise control ratio (Rn) from the estimated DNSE at an observer site, the design goal, and a safety factor. A safety factor of 1.5 is suggested for general use, and is incorporated into these formulas. However, the safety factor for each project should be considered on its own merits. The required noise control ratio is:

$$Rn(L) = 1.5 \times DNSE(DG)/DNSE(L) \qquad \text{[Eq 31]}$$

where DNSE(DG) is the design goal DNSE.

2. Determine the required barrier performance at the observer site by vehicle type from:

$$Fb(L,TYPE) = Rn(L) x Ko(L,TYPE) x [Do(L)/15] \qquad \text{[Eq 32]}$$

3. Select the Fb associated with the vehicle type that has the highest source height, Hs (Table 7 contains source heights), and the Fb associated with the vehicle having the greatest partial DNSE(L) (Line L of worksheet). These two values normally should bound the required design input value. If the minimum required value of Fb is more than 0.25, set it equal to 0.25 and set the corresponding Fresnel number of 0.1. (Note: if there are several observer sites, the site with the smallest set of Fb values should be used. Also, if a sound-absorptive earth berm is being considered, multiply Fb by 2.0.)

4. Estimate the Fresnel numbers, No(L,TYPE), required to obtain Fb(L,TYPE) for the vehicle types selected as bonding values in step three. Use Figure 11 to estimate Fb(L,TYPE).

Table 7

Vehicle Source and Observer Heights*

Vehicle Type	Source Height Relative to Road Elevations (m)
AA**	0.0
AC	0.0
MT	0.7
HT	2.4
AT	2.4
TT	1.0
T	1.0

*The observer height relative to local terrain for people outdoors and on first floors is usually assumed to be 1.5 m. If observer site is on an upper floor of a multi-story building, add 3 m per floor to the 1.5-m, first-floor, height.
**Abbreviations as in Chapter 3.

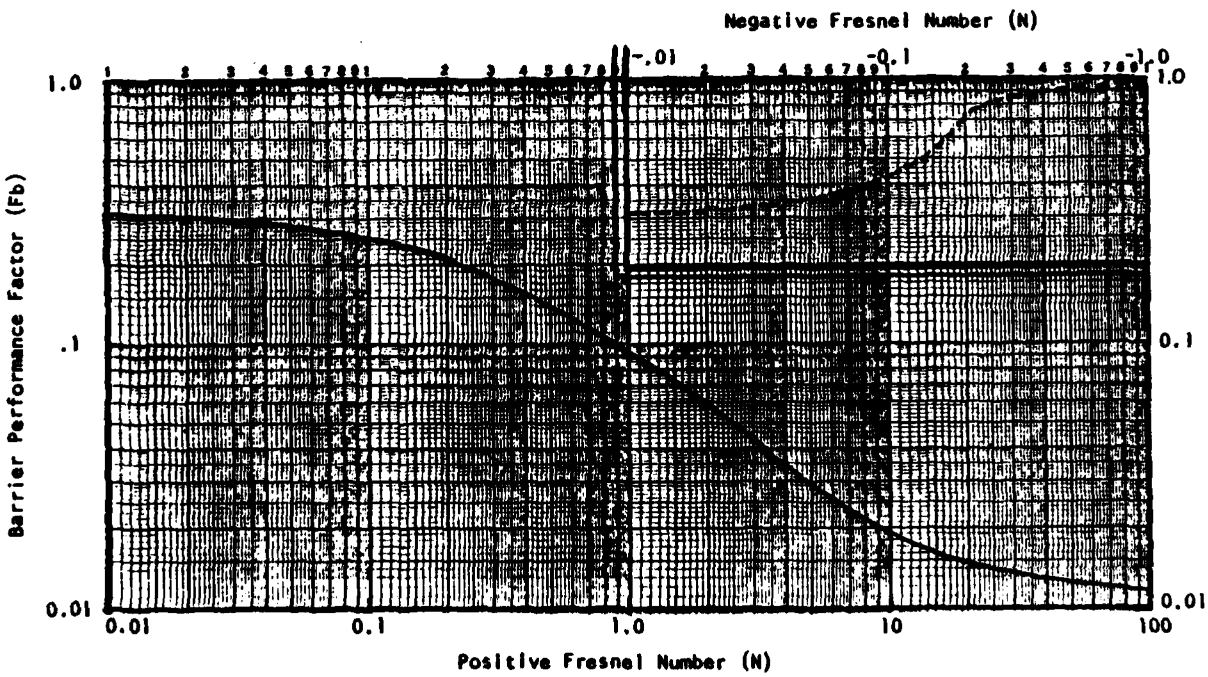


Figure 11. Barrier performance factor as a function of Fresnel number (N). Use Equations 36 through 39 for more accuracy.

5. Select trial sites for the barrier and associated values of the source-barrier distance (Db). For each trial site, and each of the two vehicle types obtain the approximate relationships between No(L,TYPE), the barrier break distance B(L,TYPE), the observer distances (Do), and the source barrier distance Db from:

$$B(L,TYPE) = \{[No(L,TYPE)/1.6] x Db x (1-Db/Do)\}^{.5} \qquad [Eq\ 33]$$

6. Determine the trial barrier heights for each of the two vehicle types required to achieve the desired break distance by:

$$Hb(L) = B(L,TYPE) + Hs(TYPE) x (1-Db/Do) + Ho \times Db/Do \qquad [Eq\ 34]$$

where Ho is the observer height.

7. Compare the end lengths $L(Db,85^{o})$ of the various design alternatives, assuming an 85^{o} end angle, from:

$$L(Db,85^{o}) = 11.4 \times (Do - Db) \qquad [Eq\ 35]$$

Figure 11 indicates how long each alternative must be.

8. For each trial design alternative, proceed to Step X and calculate its barrier performance relative to the required performance in 1 above. Once an alternative is found to meet performance requirements for these two (or one) vehicle categories, make a complete calculation for all vehicle types. If necessary, adjust the break distance and recalculate, continuing an iterative process until the design meets the requirements. Repeat this procedure with the other design alternatives, then select the most suitable.

Steps X, Y, and Z: Barrier, Source, and Observer Site Geometry

The source heights to be used in barrier design calculations and suggested observer heights are given in Table 7.

Initial Screen. Barrier designs analyzed with the Initial Screen method are considered to be only preliminary approximations because of the method's simplifications--in particular, the combination of all traffic in the near lane and the assumption of flat terrain. The method is as follows.

Determine the distance (Db) between the barrier and the source (Figure 12). For each vehicle type, calculate the break distance, B(LTYPE), the distance by which the barrier extends above and breaks the line of site; see Figure 12:

$$B(L,TYPE) = Hb - Ho \times Db/Do - Hs(TYPE) \times (1-Db/Do) \qquad [Eq\ 36]$$

Then proceed to Step AA.

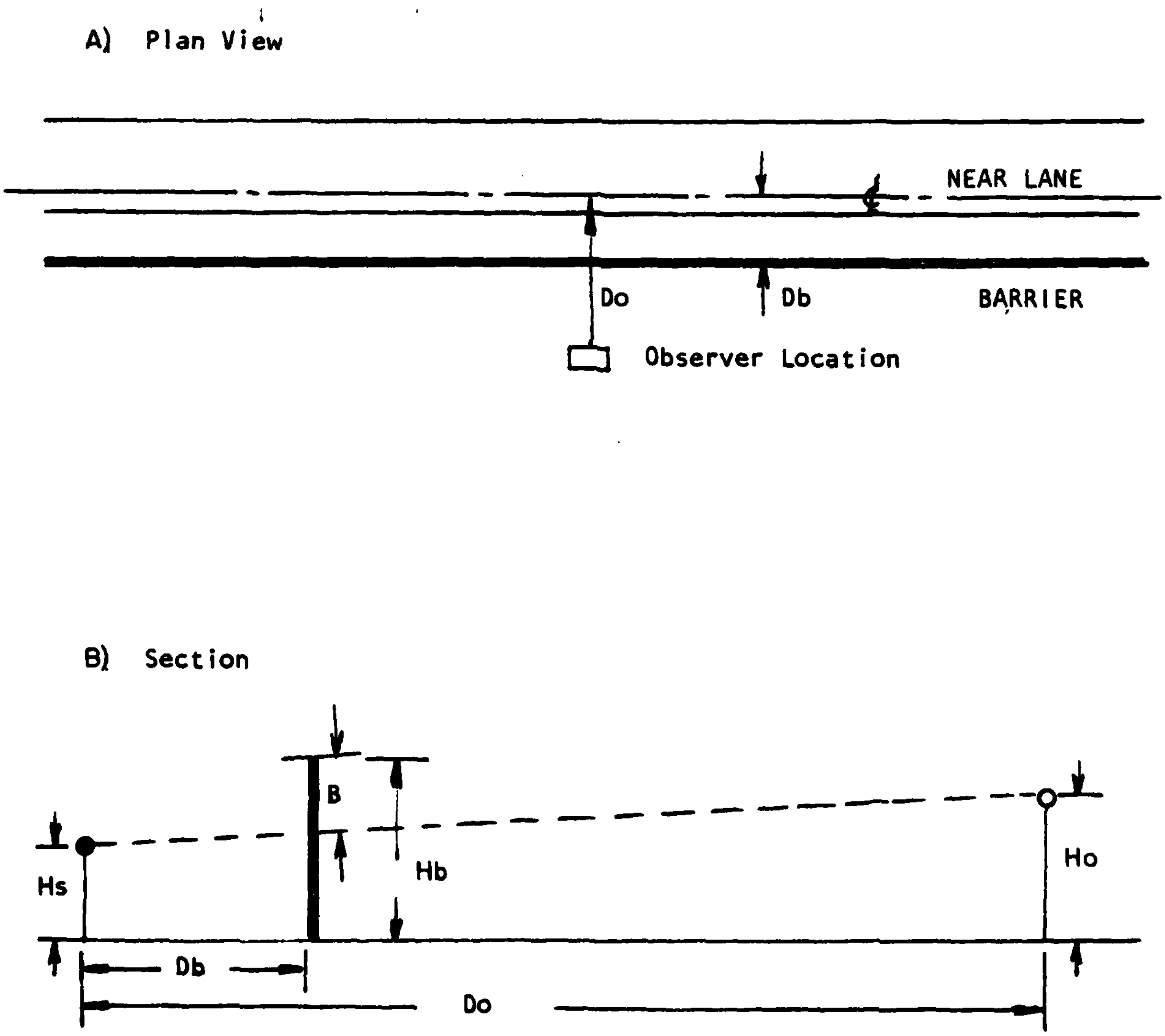


Figure 12. Barrier geometry for the Initial Screen method.

Simple Site. Determine the distance (Db) between the barrier and the source (Figure 13). For each vehicle type, calculate the break distance, B, the distance by which the barrier (or shielding terrain) extends above the line of sight (L/S). Note that the break distance is measured perpendicular to the L/S. Therefore, Equation 36 should not be used if the angle between the line of sight and the horizontal exceeds approximately 10^{o}. Source heights and suggested observer heights are given in Table 7. Proceed to Step AA.

Complex Site. For each segment (s), determine the distances (Db[s]) between the barrier and the source. Note that if the traffic fails the test in Step J it will be necessary to determine each lane separately and sum the results (Figure 14). Also for each segment, determine the barrier end angles (θR and θL). In most situations, these angles will be identical to the segment end angles, unless the barrier geometry deviates significantly from the road segments' geometry. If there are significant deviations, it may be necessary to subdivide the roadway with additional segments.

In some situations (including the Simple Site geometry), the end of the barrier will be at a finite distance with an angle (ΦL) less than 90^{o}, whereas the last road segment may extend to infinity with an angle (θL) of 90^{o}. In this event, θL should be defined by the barrier end, with the segment redefined accordingly. For each vehicle type, calculate the break distance, B, using the method described for the Simple Site method.

Step AA: Path Length Difference and Fresnel Number

The path length difference (Po) for each vehicle type between the path over the barrier and the line of sight distance perpendicular to the road (Figure 15) is calculated from:

$$Po = D1 + D2 - D3 \qquad \text{[Eq 37]}$$

For the most practical situations when the break distance (B) is less than 30 percent of the shortest distance to the barrier from either the source (Db), or the observer (Do-Db), the path length difference is:

$$Po = B^2 \times Do \,/\, 2\times[Db \times (Do-Db)] \qquad \text{[Eq 38]}$$

The Fresnel number (N) for sound radiated from each vehicle type along the perpendicular between the observer and the road is:

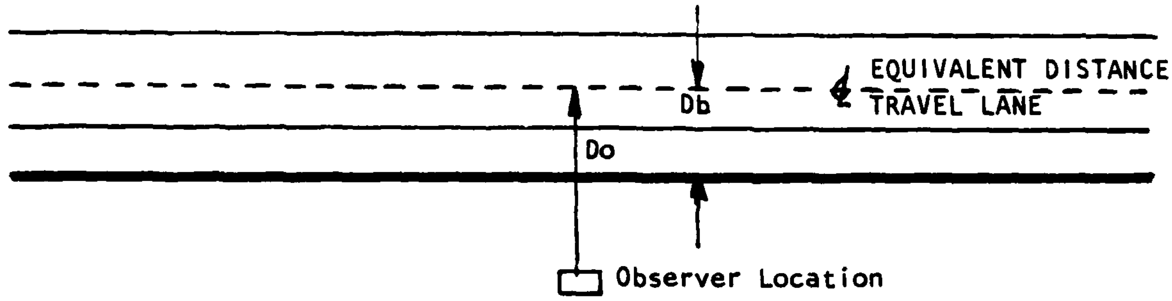
$$N = 2\ Po \times F/C$$

where F is the frequency and C is the velocity of sound in air (approximately 344 m/s).

In the metric system, with an assumed effective center frequency of 550 Hz,

$$N = 3.2\ Po = 1.6\times B^2\times Do/[Db\times(Do-Db)] \qquad \text{[Eq 39]}$$

A) Plan View



B) Section Sketches

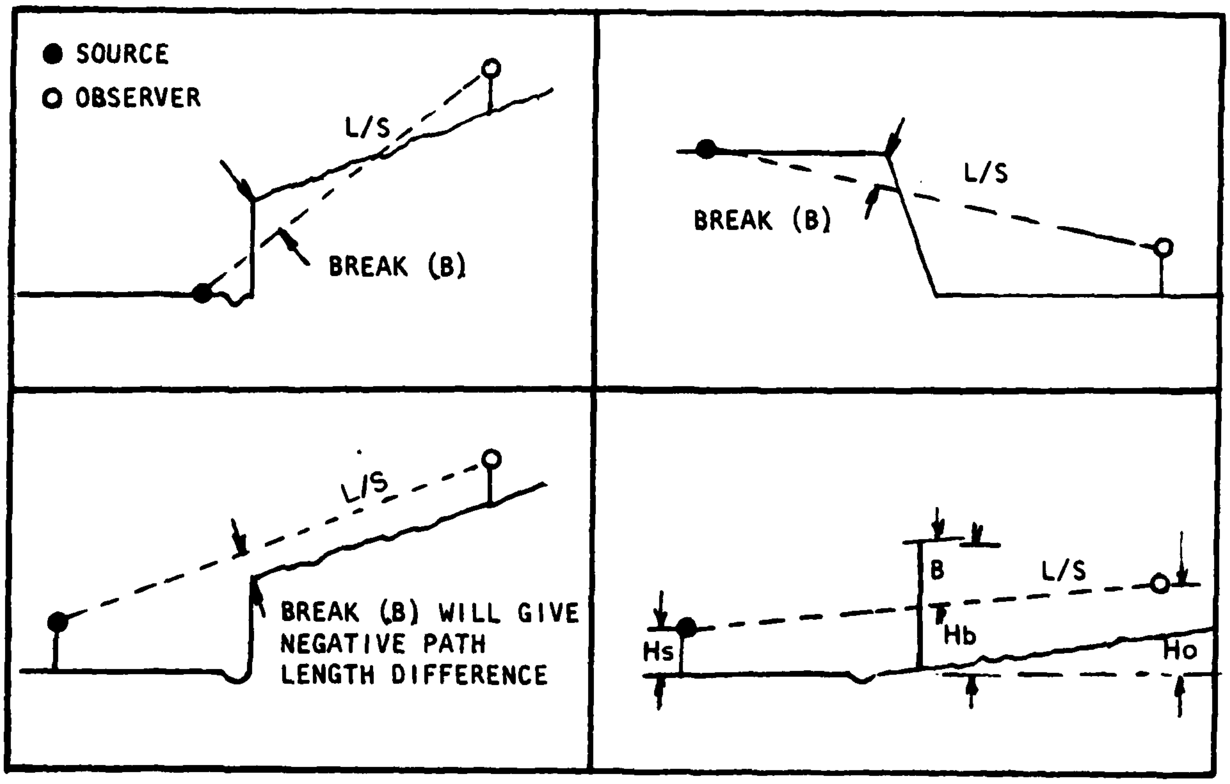


Figure 13. Geometry for Simple Site method (see also section in Figure 12).

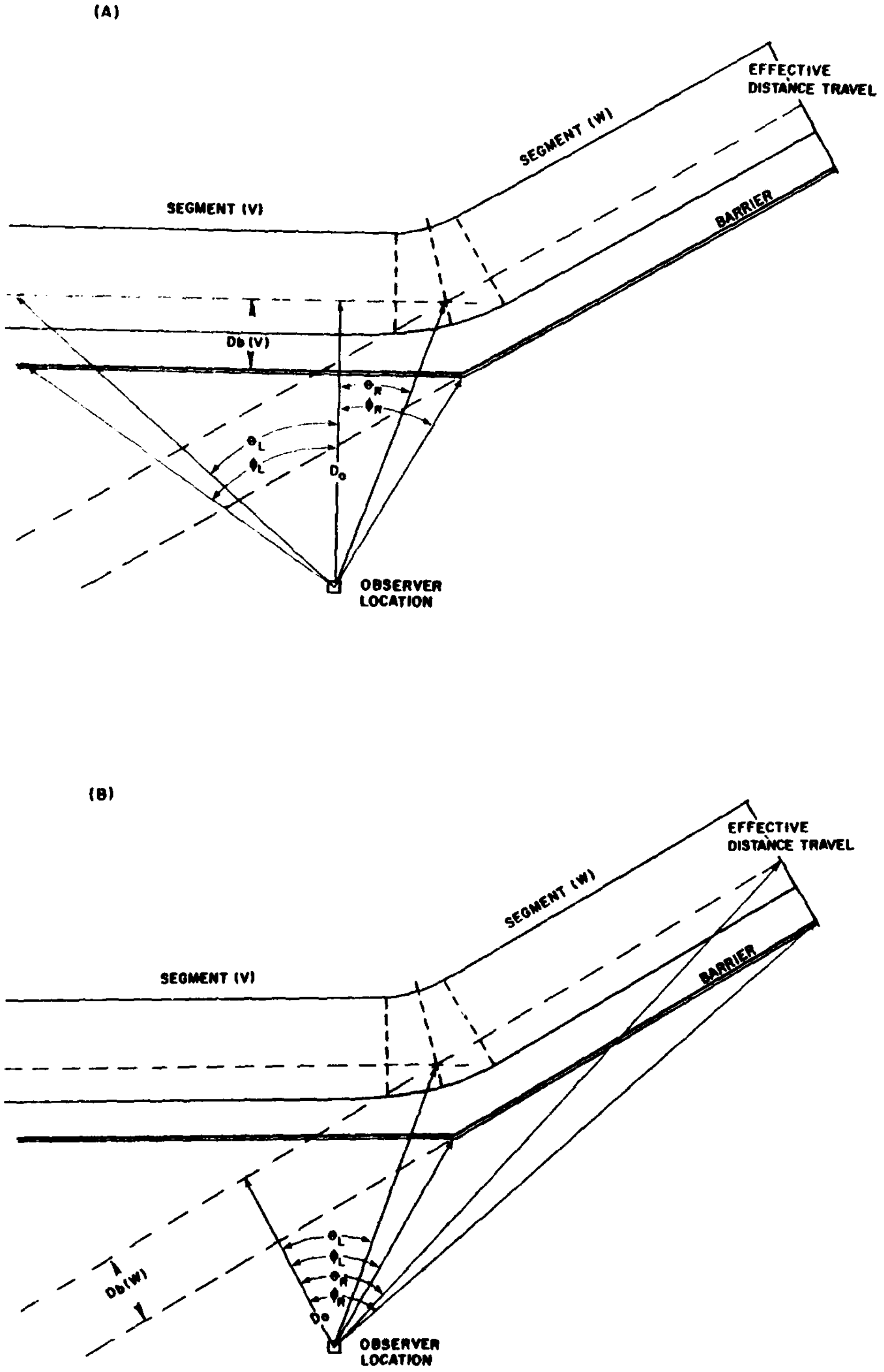
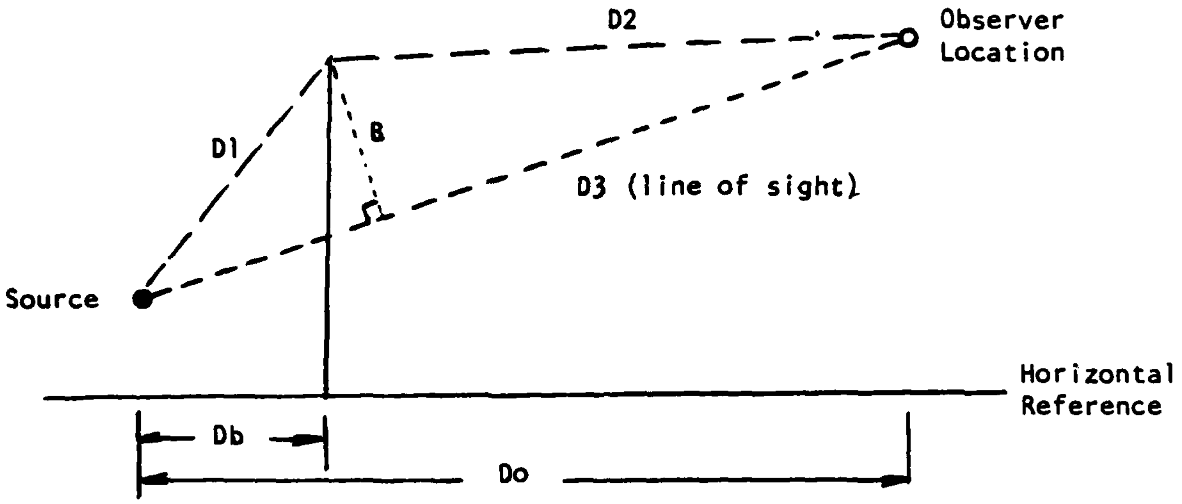


Figure 14. Complex Site geometry (see also inset in Figure 11).



Path length difference Po = D1 + D2 − D3   [Eq 32]

NOTE: The break is measured perpendicular to the line of sight. If the line of sight angle with the horizontal exceeds approximately 10°, Equations 30 and 31 should not be used and B should be calculated directly from the geometry. Also, when B exceeds 30 percent of the shortest distance, Db or (Do − DB), to the barrier, Equation 33 should not be used and Po should be calculated directly from the geometry.

Figure 15. Barrier path length differences.

Note: the Fresnel number can be negative (Figures 11 and 13). In this event, the barrier transmission factor ranges between 1.0 and 0.3, with the latter value obtained when the break distance is zero.

Step AB: Barrier Transmission Factor to Observer Site

The barrier transmission factor for each vehicle type to an observer location (Tb) is obtained by multiplying the barrier performance factor Fb(N), which is a function of the Fresnel number (N), by a term representing the spreading of sound with distances. It also contains a factor (E) that accounts for the sound absorption on the roadway side of an earth berm, if present. Thus:

$$Tb(L,TYPE) = E \times Fb(N) \times (Do/15)^{-1} \qquad \text{[Eq 40]}$$

where E = 0.5 for a barrier that consists partially of an earth berm with ground absorption on its roadway side, or:

= 1.0, otherwise.

The barrier performance factor (Fb) is summarized in Figure 11 for both positive and negative values of N. The equations for Fb are summarized in Table 8. Note: when this step is used to compute a shielding transmission factor (Ks), substitute Ks for Fb.

Initial Screen. Use Figure 11 or the appropriate equation in Table 8 to obtain the barrier performance factors (Fb[L,TYPE]) for each vehicle type. Then obtain the associated barrier transmission factors (Tb[TYPE]) and the observer location using Equation 40. Proceed to Step AC.

Simple Site. Use the appropriate equation in Table 8 (or, for preliminary design, use Figure 11) to obtain at each observer location (L) and vehicle type (TYPE) the barrier performance factors Fb(L,TYPE). Then use Equation 40 to obtain the associated barrier transmission factors.

These results are essentially valid as long as the barrier ends make an angle of $\pm 85^{\circ}$ with the perpendicular line from the observer site to the roadway. If the absolute value of one or both of the end angles is less than 85° and if the barrier is not symmetrical, the Complex Site method should be used. This allows for addition of "end segments" to the analysis to describe the noise transmitted around the ends of the barrier. The Complex Site method should also be used if the barrier is essentially symmetrical with a barrier performance value of less than 0.1 and ground absorption.

If the barrier is essentially symmetrical, with the absolute value of the end angles (ΦR and ΦL) less than 85°, do the following substeps.

1. Select the lesser of the absolute values of the two end angles to be Φ.

2. Calculate:

$$N(\Phi) = 1.06 \times N \times (90 - \Phi)/90 \qquad \text{[Eq 48]}$$

Table 8

Barrier Performance Factors* for the Fresnel Number (N)

Fresnel Number Range	Equation**	
For N positive		
$0 \leq N < 0.02$	$Fb = 0.3162 - 0.5575\ N$	[Eq 41]
$0.02 \leq N < 5.0$	$Fb = 10^{-[1.027+0.5854 \log N + 0.1674(\log N)^2]}$	[Eq 42]
$5.0 \leq N < 100$	$Fb = 10^{-[0.9220+1.0446 \log N - 0.2684(\log N)^2]}$	[Eq 43]
$N > 100$	$Fb = 0.011545\ [1+0.1545(1-100/N)]^{-1}$	[Eq 44]
For N negative		
$-0.02 \leq N < 0$	$Fb = 0.3192$	[Eq 45]
$-0.364 \leq N < -0.02$	$Fb = 10^{-[4.0926+10.7124 \log N + 3.1693(\log N)^2]}$	[Eq 46]
$N < -0.364$	$Fb = 0$	[Eq 47]

*All logs are to the base 10.
**Any type of N (e.g., N, N(O), and N[L,TYPE]) can be substituted for N in these equations.

3. Compute Fb(L,TYPE, |Φ|) using N(|Φ|) in place of N in the appropriate equation in Table 8 (and also Fb[L,TYPE] using N, if it was previously estimated from the figures).

4. Calculate the refined finite barrier performance factor (Fbr) from:

$$Fbr(L,TYPE, \Phi) = [90\ Fb(L,TYPE) - (90 - \Phi)\ Fb(L,TYPE, \Phi)]/90 \quad \text{[Eq 49]}$$

5. Calculate the refined barrier transmission factor (Tbr) by adding to Fb the transmission factor (90 - Φ)/90 for noise from beyond the barrier ends. Thus:

$$Tbr(L,TYPE) = [E[Fbr(L,TYPE) \times \Phi/90] + (90- \Phi)/90](15/Do) \quad \text{[Eq 50]}$$

where E = .5 if the barrier is partly an earth berm with ground absorption on its roadway side; E = 1.0 otherwise.

Complex Site. Use the appropriate equation in Table 8 to obtain the barrier performance factor Fb(L,TYPE) for each segment, each observer location

(L), and each vehicle type (TYPE). This performance factor applies to a barrier that extends between -90° and $+90^{\circ}$, or 0 to 90° for the Fresnel number (N). To obtain the performance factor that applies to the segment with end angles (ΦR and ΦL), do the following:

1. Compute $N(\Phi R)$ and $N(\Phi L)$ from:

$$N(\Phi) = 1.06 \times N \times (90 - |\Phi|)/90 \qquad \text{[Eq 51]}$$

2. Compute the segment Fb when ΦR and ΦL have the same sign:

$$Fb(\Phi R, \Phi L) = \{(90 - |\Phi L|)Fb(\Phi L) - (90 - |\Phi R|)Fb(\Phi R)\}/(\Phi R - \Phi L) \qquad \text{[Eq 52]}$$

and when ΦR is positive and ΦL is negative:

$$Fb(\Phi R,\Phi L) = [180\ Fb(N)-(90 - \Phi R)-(90 - |\Phi L|)\ Fb(\Phi L)]/(\Phi R - \Phi L)$$

3. For the segment, location, and vehicle type, the barrier transmission is obtained from:

$$Tb(S,L,TYPE) = E \times (\Phi R - \Phi L) \times Fb(\Phi R,\Phi L)/(180xDo/15) \qquad [53]$$

where E = .5 if the barrier is partly an earth berm with ground absorption on its roadway side and E=1.0 otherwise.

Step AC: Observer Location Day-Night Sound Exposure With Noise Barrier

The observer location DNSE is calculated from the partial DNSE(L,TYPE) values for each type, as follows:

$$PDNSE(L,TYPE) = Tb(L,TYPE) \times PDNSE(15) \qquad \text{[Eq 54]}$$

$$DNSE(L) = \sum_{\text{ALL TYPES}} PDNSE(S,L,TYPE) \qquad \text{[Eq 55]}$$

Compare the results with the design goal, divided by the safety factor, and iterate the alternative designs as appropriate.

Complex Site. Use Equation 54 to compute PDNSE(S,L,TYPE) for each segment (s). Then compute DNSE(S,L) using Equation 14 with PDNSE(S,L,TYPE). Combine the segment values to obtain the total observer location DNSE(L) with the noise barrier using:

$$DNSE(L) = \sum_{\text{ALL SEGMENTS}} DNSE(S,L) \qquad \text{[Eq 56]}$$

Compare the results at the various locations with the design goal, divided by the safety factor, and iterate as appropriate.

5 APPLICATIONS OF THE PROCEDURE

This chapter gives several examples illustrating uses for the three methods. Seven scenarios use a straight section of four-lane roadway and one scenario incorporates curves that require the complex site method.

Initial Screen and Simple Site Methods

Figure 16 shows the site geometry for scenarios 1 through 7. The road is assumed to have a 14.67-m width and a 12-m right-of-way. There are six homes on 100-m-wide lots with backs toward the roadway. The pertinent variables for these seven scenarios are summarized in Table 9 and the sample worksheets for these cases are shown in Figures 17 through 21. Calculations should be checked against the results on the worksheet. The interpretation of these results is discussed below.

Scenarios 1 and 2 (Figure 17)

The DNSE at 15 m was less than one-half the design goal, and the actual observer distance was greater than 15 m. Therefore, the noise at the observer site for the first scenario is judged to be less than the design goal. Therefore, no barrier is required.

The second scenario added Army trucks to the automobiles in the first scenario. The Initial Screen showed that the DNSE at the observer site was slightly greater than the design goal. Therefore, a more detailed calculation was made with the Simple Site Method. It was necessary to calculate separately for both traffic directions because the directional traffic ratio for Army trucks was outside the limits permitted for use of a single equivalent travel line. The results of the Simple Site analy found the observer site to be within the design goal.

Scenario 3 (Figure 18)

This scenario is like the second one, except that ground absorption was added and the day-night mix of Army trucks was made identical in both directions. The addition of an absorbing ground cover noticeably reduced the observer site DNSE (compare with Figure 17). However, the reduction was not enough to bring the result to less than one-half the design goal, so it was necessary to use the Simple Site method.

Because the Army truck traffic day-night ratio was the same in both directions, the Directional Traffic Ratio for both trucks and autos was within limits for analysis using the equivalent method. The results showed that the site was within the design goal.

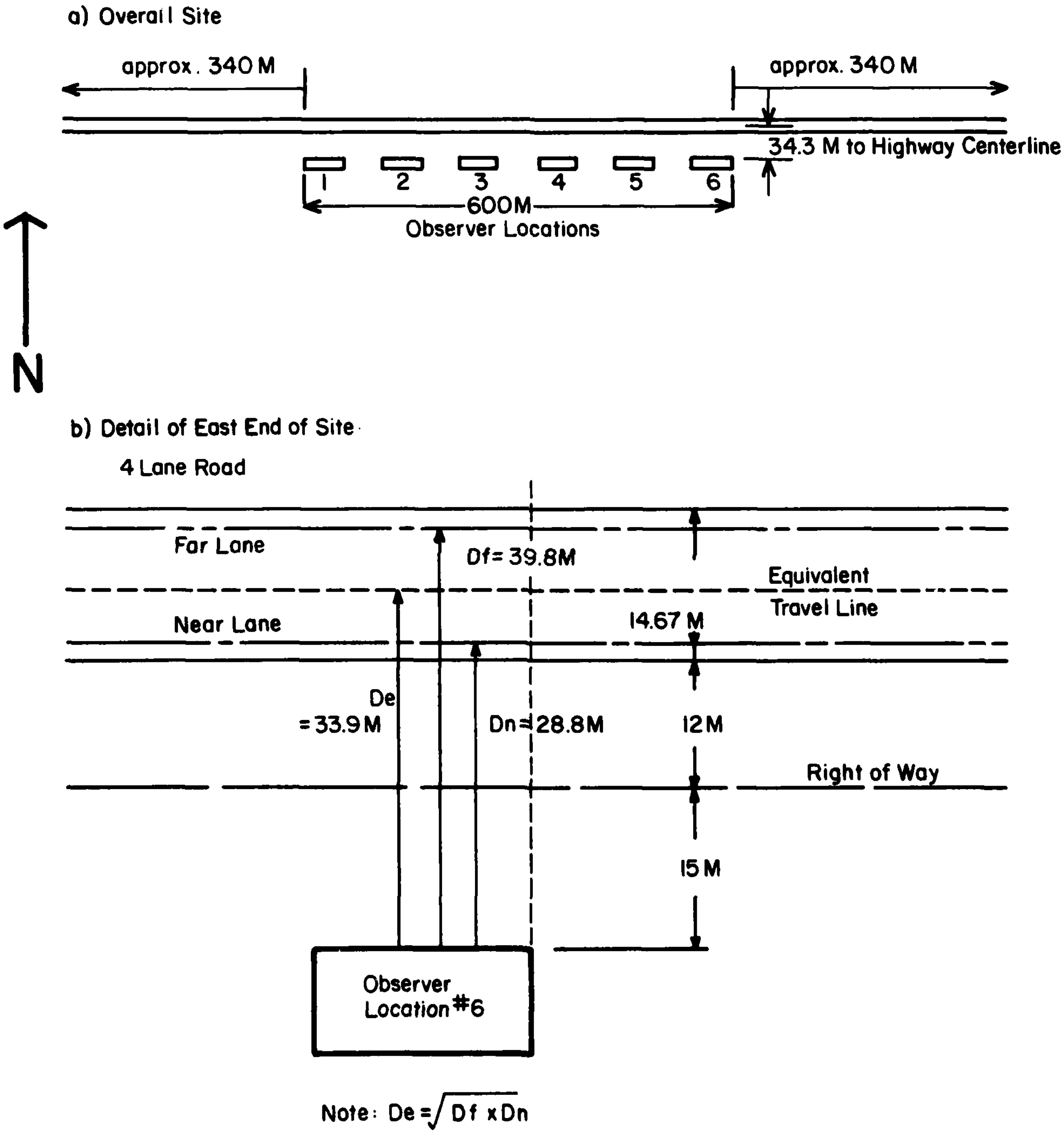


Figure 16. General site plan for scenarios 1 through 7, except that the distance from the observer to the right-of-way is increased from 15 to 100 m.

Table 9

Summary of Scenarios for Examples 1 Through 7

Item	Example 1	2		3		4		5		6		7	
Design Goal (pasques)	100	100		100		100		100		10		10	
Vehicle Types*	AC	AC	AT	AC	AT	AC	AT	AC	AT	AC	AT	AC	AT
# Eastbound: Day	2300	2300	500	2300	450	2300	500	2300	400	2300	400	2300	400
Night	400	400	0	400	50	400	0	400	100	400	100	400	100
# Westbound: Day	2500	2500	400	2500	450	2500	400	2500	500	2500	500	2500	500
Night	200	200	100	200	50	200	100	200	0	200	0	200	0
Gradient	0	0		0		+5% East		+5% East		+5% East		+5% East	
Backyard Distance: m	15	15		15		15		15		15		15	
Ground Absorption	None	None		Yes		Yes		Yes		Yes		Yes	
Conclusion	Screen-ed out at 15 m	OK, using Single Site method		OK, using Single Site method with equiva-lent lane		OK, using Simple Site method		Requires barrier, H_b=2.67 m		Requires 2-m-high absorbing berm plus 3-m-high wall		Requires a 3.06-m-high barrier	

*As defined in Chapter 3.

ITEM	1. INITIAL	2. INITIAL		2. SIMPLE SITE				TOTAL
A) ROAD SEGMENT NO.; LANE IDENTITY	ROAD A	ROAD A		ROAD A, EAST		ROAD A, WEST		
B) DESIGN GOAL D/N SOUND EXPOSURE (DNSE), PASQUES	100	100		100				
C) VEHICLE TYPES (AA, AC, MT, HT, AT, TT AND TW)	AC	AC	AT	AC	AT	AC	AT	
D) VEHICLE VELOCITY, KMH	50	50	50	50	50	50	50	
E) SINGLE VEHICLE SOUND EXPOSURE (SE), PASQUES	2.5×10^{-3}	2.5×10^{-3}	0.1	2.77×10^{-3}	0.1	2.77×10^{-3}	0.1	
F) GRADIENT (Y OR N); VALUE (%); & NOISE FACTORS (Fu+Fd)	N	N		N				
G) AVG. NO. OF VEHICLES IN DAY (0700-2200) (Nd)	4800	4800	900	2300	500	2500	400	
H) AVG. NO. OF VEHICLES AT NIGHT (2200-0700) (Nn)	600	600	100	400	0	200	100	
I) AVG. EFFECTIVE NO. OF VEHICLES (Nd+10Nn)=Ne	10800	10800	1900	6300	500	4500	1400	
J) DIRECTIONAL TRAFFIC RATIO, 0.7<R<1.5 (Y OR N?)				Y	N	Y	N	
K) DIRECTIONAL VELOCITY RATIO, 0.8<R<1.2 (Y OR N?)				Y	Y	Y	Y	
L) PARTIAL D/N SOUND EXPOSURE AT 15 M, PASQUES	27.0	27.0	1900	17.45	50.0	12.47	140.0	
TOTAL DNSE (PASQUES)	27.0	217.0		67.45		152.47		
M) OBSERVER DISTS. TO NEAR & FAR LANES (Df, Dn), M	OK	28.8, 39.8		28.8		39.8		
N) FAR, NEAR LANE DIST. RATIO, Df/Dn<=2 (Y OR N?)				Y				
O) OBSERVER DIST. (Do), EITHER Df OR Dn, OR De		28.8		28.8		39.8		
P) SEGMENT END ANGLES (θL & θR), DEG.								
Q) VEGETATION TRANSMISSION FACTOR (Kw)		1.0		1.0				
R) BUILDING ROW TRANSMISSION FACTOR (Kh)		1.0		1.0				
S) SHIELDING TRANSMISSION FACTOR (Ks)				1.0 →				
T) BASELINE TRANSMISSION FACTOR (QxRxS) = Kc		1.0		1.0 →				
U) GROUND ABSORPTION (a); ANGULAR PROP. FACTOR (Ka)		1.0		1.0				
V) TRANSMISSION FACTOR (SMALLER OF U & T)x(Do/15)$^{-1}$ = Ko		.52		.52 →		.38 →		
W) OBSERVER BASELINE DNSE(L), PASQUES		14.1	98.8	35.1 →		57.4 →		
TOTAL DNSE (PASQUES)		112.9		92.5				
X) BARRIER DIST. TO SOURCE (Db), M				0				
Y) BREAK DIST. IN LINE OF SIGHT (B), M								
Z) BARRIER END ANGLES (βL & βR), DEG.								
AA) PATH LENGTH DIFFERENCE (Po), M; FRESNEL NO. (No)								
AB) BARRIER TRANSMISSION FACTOR (Fb)x(Do/15)-1								
AC) OBSERVER DNSE(L) WITH BARRIER, PASQUES								
TOTAL DNSE (PASQUES)								

Figure 17. Examples of the procedure for scenarios 1 and 2.

ITEM	3. INITIAL		3. SIMPLE SITE						TOTAL
A) ROAD SEGMENT NO.; LANE IDENTITY	ROAD A		ROAD A EAST		ROAD A WEST		EQUIVALENT		
B) DESIGN GOAL D/N SOUND EXPOSURE (DNSE), PASQUES	100		100				100		
C) VEHICLE TYPES (AA, AC, MT, HT, AT, TT AND TW)	AC	AT	AC	AT	AC	AT	AC	AT	
D) VEHICLE VELOCITY, KMH	50	50	50	50	50	50	50	50	
E) SINGLE VEHICLE SOUND EXPOSURE (SE), PASQUES	2.5×10^{-3}	0.1	2.77×10^{-3}	0.1	2.77×10^{-3}	0.1	2.77×10^{-3}	0.1	
F) GRADIENT (Y OR N); VALUE (%); & NOISE FACTORS (Fu+Fd)	N		N				N		
G) AVG. NO. OF VEHICLES IN DAY (0700-2200) (Nd)	4800	900	2300	450	2500	450	4800	900	
H) AVG. NO. OF VEHICLES AT NIGHT (2200-0700) (Nn)	600	100	400	50	200	200	600	100	
I) AVG. EFFECTIVE NO. OF VEHICLES (Nd+10Nn)=Ne	10800	1900	6300	950	4500	4500	10800	1900	
J) DIRECTIONAL TRAFFIC RATIO, 0.7<R<1.5 (Y OR N?)			Y	Y	Y	Y			
K) DIRECTIONAL VELOCITY RATIO, 0.8<R<1.2 (Y OR N?)			Y	Y	Y	Y			
L) PARTIAL D/N SOUND EXPOSURE AT 15 M, PASQUES	27.0	190.0	1	95.0			29.92	19.0	
TOTAL DNSE (PASQUES)	217.0		112.45		107.47		219.92		
M) OBSERVER DISTS. TO NEAR & FAR LANES (Df, Dn), M	28.8, 39.8		28.8		39.8				
N) FAR, NEAR LANE DIST. RATIO, Df/Dn<=2 (Y OR N?)			Y, USE EQUIVALENT						
O) OBSERVER DIST. (Do), EITHER Df OR Dn, OR De	28.8						33.86		
P) SEGMENT END ANGLES (ΘL & ΘR), DEG.									
Q) VEGETATION TRANSMISSION FACTOR (Kw)	1.0						1.0		
R) BUILDING ROW TRANSMISSION FACTOR (Kh)	1.0						1.0		
S) SHIELDING TRANSMISSION FACTOR (Ks)							1.0 →		
T) BASELINE TRANSMISSION FACTOR (QxRxS) = Kc	1.0						1.0 →		
U) GROUND ABSORPTION (a); ANGULAR PROP. FACTOR (Ka)	.72						.67		
V) TRANSMISSION FACTOR (SMALLER OF U & T)x(Do/15)$^{-1}$ = Ka	.38 →						.030 →		
W) OBSERVER BASELINE DNSE(L), PASQUES	10.1	71.4							
TOTAL DNSE (PASQUES)	81.6						65.27		
X) BARRIER DIST. TO SOURCE (Db), M							OK		
Y) BREAK DIST. IN LINE OF SIGHT (B), M									
Z) BARRIER END ANGLES (ØL & ØR), DEG.									
AA) PATH LENGTH DIFFERENCE (Po), M; FRESNEL NO. (No)									
AB) BARRIER TRANSMISSION FACTOR (Fb)x(Do/15)-1									
AC) OBSERVER DNSE(L) WITH BARRIER, PASQUES									
TOTAL DNSE (PASQUES)									

Figure 18. Examples of the procedure for scenario 3.

Scenarios 4 and 5 (Figure 19)

Scenario 4 retains the ground absorption from scenario 3, returns to the truck Directional Traffic Ratio of number 2, and adds a 5 percent gradient that rises toward the east. The DNSE at the observer site is excessive with the initial screen, but acceptable when analyzed with the Simple Site Method. (Note: the Initial Screen is a very worthwhile tool in practice. Here, the examples are deliberately designed to require additional analysis and show the relationships between the various results.)

Scenario 5 is the same as scenario 4 except that the direction of the night truck traffic is reversed so it goes uphill toward the east. The Initial Screen is identical for both cases. The results from the Simple Site analysis show the sound exposure to be doubled from scenario 4, and that a barrier is required.

Preliminary design analysis showed that the required barrier performance factor was more than the maximum value of 0.25 so the latter was used, together with a Fresnel number of 0.1. The barrier requirements were estimated on a barrier located close to the pavement (3.55 m to pavement edge and Db = 5 m) and on a barrier located at the edge of the right-of-way (Db - 13.8 m). The barrier height requirements were almost identical (2.66 m for the Db = 5 m and 2.76 m for Db = 13.8). However, the end extensions of the barrier needed to get to 85^{o} were much longer for the barrier near the highway (272 vs 171 m). Therefore, the location at the edge of the right-of-way was chosen and used for the data developed in Figure 19.

The predicted DNSE with the barrier is 52.6 pasques which is slightly less than the design goal and 100 divided by a safety factor of 1.5. The barrier could probably be shortened somewhat from its total length of 942 m (171 + 600 + 171), and should be checked using the Complex Site method.

Scenarios 6 and 7 (Figure 20)

Scenario 6 is identical to scenario 5 except that the design goal noise has been reduced to 10 pasques from the 100 pasques in scenario 5. The DNSE of 164 pasques at the observer site are the same as obtained in 5 but the barrier requirements are much greater.

Preliminary design indicated that barriers placed in the right-of-way would need to be 5.87 to 6.72 m high. To avoid such a high barrier, a combination was chosen that consisted of an earth berm (2-m height) and barrier wall (3-m height). The road side of the earth berm was assumed to be landscaped with sound-absorbent ground cover so it would reduce the noise by 0.5 (E = .5). The barrier was placed toward the rear of the right-of-way with Db = 9.8 m.

Scenario 7 is the same as that for number 6 except that the houses are assumed to be 85 m farther from the highway. The Initial Screen showed that the DNSE probably exceeded the design goal of 10 pasques. Further analysis by the Simple Site method confirmed this suggestion.

ITEM	4. INITIAL			4. SIMPLE SITE				5. INITIAL		5. SIMPLE SITE				TOTAL
A) ROAD SEGMENT NO.; LANE IDENTITY	ROAD A			ROAD A, EAST		ROAD A, WEST		SAME		ROAD A, EAST		ROAD A, WEST		
B) DESIGN GOAL D/N SOUND EXPOSURE (DNSE), PASQUES	10^6			100				AS 4		100				
C) VEHICLE TYPES (AA, AC, MT, HT, AT, TT AND TW)	AC	AT		AC	AT	AC	AT			AC	AT	AC	AT	
D) VEHICLE VELOCITY, KMH	50	50		50	50	50	50			50	50	50	50	
E) SINGLE VEHICLE SOUND EXPOSURE (SE), PASQUES	2.5×10^{-3}	0.1		2.77×10^{-3}	0.1	2.77×10^{-3}	0.1			2.77×10^{-3}	0.1	2.73×10^{-3}	0.1	
F) GRADIENT (Y OR N); VALUE (%); & NOISE FACTORS (Fu+Fd)	1.58 (EAST)			5%, 2.65		-5%, 0.38				5%, 2.65		-5%, 0.38		
G) AVG. NO. OF VEHICLES IN DAY (0700-2200) (Nd)	4800	900		2300	500	2500	400			2300	400	2500	500	
H) AVG. NO. OF VEHICLES AT NIGHT (2200-0700) (Nn)	600	100		400	0	200	100			400	100	200	0	
I) AVG. EFFECTIVE NO. OF VEHICLES (Nd+10Nn)=Ne	10800	1900		6300	500	4500	1400			6300	1400	4500	500	
J) DIRECTIONAL TRAFFIC RATIO, 0.7<R<1.5 (Y OR N?)				Y	N	Y	N			Y	N	Y	N	
K) DIRECTIONAL VELOCITY RATIO, 0.8<R<1.2 (Y OR N?)				Y	Y	Y	Y			Y	Y	Y	Y	
L) PARTIAL D/N SOUND EXPOSURE AT 15 M, PASQUES	42.7	300.2		46.24	132.5	4.74	53.2			46.4	371.0	4.74	19.0	
TOTAL DNSE (PASQUES)	342.8			178.74		57.94		342.8		417.24		23.74		
M) OBSERVER DISTS. TO NEAR & FAR LANES (Df, Dn), M	28.8, 39.8			28.8		39.8				28.8		39.8		
N) FAR, NEAR LANE DIST. RATIO, Df/Dn<=2 (Y OR N?)				Y						Y				
O) OBSERVER DIST. (Do), EITHER Df OR Dn, OR De	28.5			28.8		39.8				28.8		39.8		
P) SEGMENT END ANGLES (θL & θR), DEG.														
Q) VEGETATION TRANSMISSION FACTOR (Kw)	1.0			1.0						Y				
R) BUILDING ROW TRANSMISSION FACTOR (Kh)	1.0			1.0						Y				
S) SHIELDING TRANSMISSION FACTOR (Ks)				1.0 →						1.0 →				
T) BASELINE TRANSMISSION FACTOR (QxRxS) = Kc	1.0 →			1.0 →						1.0 →				
U) GROUND ABSORPTION (a); ANGULAR PROP. FACTOR (Ka)	.72			.72		.61				.72		.61		
V) TRANSMISSION FACTOR (SMALLER OF U & T)x(Do/15)$^{-1}$ = Ko	.38 →			.38 →		.23 →				.38 →		.23 →		
W) OBSERVER BASELINE DNSE(L), PASQUES	16.2	114.1		67.9		13.33				158.55		5.46		
TOTAL DNSE (PASQUES)	130.3			81.25				130.3		164.0				
X) BARRIER DIST. TO SOURCE (Db), M				OK						13.8		24.8		
Y) BREAK DIST. IN LINE OF SIGHT (B), M										1.94	.67	1.72	.82	
Z) BARRIER END ANGLES (βL & βR), DEG.										90°				
AA) PATH LENGTH DIFFERENCE (Po), M; FRESNEL NO. (No)										.83	.10	.51	.12	
AB) BARRIER TRANSMISSION FACTOR (Fb)x(Do/15)-1										.052	.13	.053	.090	
AC) OBSERVER DNSE(L) WITH BARRIER, PASQUES										2.40	48.2	0.30	1.70	
TOTAL DNSE (PASQUES)										52.6 OK				

Figure 19. Examples of the procedure for scenarios 4 and 5.

ITEM	6. SIMPLE SITE					7. INITIAL			7. SIMPLE SITE					TOTAL
A) ROAD SEGMENT NO.; LANE IDENTITY	ROAD A, EAST		ROAD A, WEST			ROAD A			ROAD A, EAST		ROAD A, WEST			
B) DESIGN GOAL D/N SOUND EXPOSURE (DNSE), PASQUES	10					10			10					
C) VEHICLE TYPES (AA, AC, MT, HT, AT, TT AND TW)	AC	AT	AC	AT		AC	AT		AC	AT	AC	AT		
D) VEHICLE VELOCITY, KMH	50	50	50	50		50	50		50	50	50	50		
E) SINGLE VEHICLE SOUND EXPOSURE (SE), PASQUES	2.77×10^{-3}	0.1	2.77×10^{-3}	0.1		2.5×10^{-3}	0.1		2.77×10^{-3}	0.1	2.77×10^{-3}	0.1		
F) GRADIENT (Y OR N); VALUE (%); & NOISE FACTORS (Fu+Fd)	5%, 2.65		-5%, 0.38			1.58 (EAST)			5%, 2.65		-5%, 0.38			
G) AVG. NO. OF VEHICLES IN DAY (0700-2200) (Nd)	7300	400	2500	500		4800	900		2300	400	2500	500		
H) AVG. NO. OF VEHICLES AT NIGHT (2200-0700) (Nn)	400	100	200	0		600	100		400	100	200	0		
I) AVG. EFFECTIVE NO. OF VEHICLES (Nd+10Nn)=Ne	6300	1400	4500	500		10800	1900		6300	1400	4500	500		
J) DIRECTIONAL TRAFFIC RATIO, 0.7<R<1.5 (Y OR N?)	Y	N	Y	N					Y	N	Y	N		
K) DIRECTIONAL VELOCITY RATIO, 0.8<R<1.2 (Y OR N?)	Y	Y	Y	Y					Y	Y	Y	Y		
L) PARTIAL D/N SOUND EXPOSURE AT 15 M, PASQUES	46.24	371.0	4.74	19.0		42.7	3005		46.24	371.0	4.74	19.0		
TOTAL DNSE (PASQUES)	417.24		23.74			347.8			417.24		23.74			
M) OBSERVER DISTS. TO NEAR & FAR LANES (Df, Dn), M	28.8		39.8			113.8	124.8		113.8		124.8			
N) FAR, NEAR LANE DIST. RATIO, Df/Dn<=2 (Y OR N?)	Y								Y					
O) OBSERVER DIST. (Do), EITHER Df OR Dn, OR De	28.8		39.8			113.8			113.8		124.8			
P) SEGMENT END ANGLES (θL & θR), DEG.														
Q) VEGETATION TRANSMISSION FACTOR (Kw)	1.0					1.0			1.0					
R) BUILDING ROW TRANSMISSION FACTOR (Kh)	1.0					1.0			1.0					
S) SHIELDING TRANSMISSION FACTOR (Ks)	1.0 →								1.0 →					
T) BASELINE TRANSMISSION FACTOR (QxRxS) = Kc	1.0 →					1.0 →			1.0 →					
U) GROUND ABSORPTION (a); ANGULAR PROP. FACTOR (Ka)	.72		.61			.36			.36		.35			
V) TRANSMISSION FACTOR (SMALLER OF U & T)x(Do/15)$^{-1}$ = Ko	.38 →		.23 →			.047 →			.047 →		.042 →			
W) OBSERVER BASELINE DNSE(L), PASQUES	158.55		5.46						2.17	17.44	.20	.80		
TOTAL DNSE (PASQUES)	164.0					16.1			70.61					
X) BARRIER DIST. TO SOURCE (Db), M	9.8		20.8						5.0		16.0			
Y) BREAK DIST. IN LINE OF SIGHT (B), M	4.45	2.34	4.18	3.01					3.79	1.50	3.67	1.58		
Z) BARRIER END ANGLES (θL & θR), DEG.	90° →								90° →					
AA) PATH LENGTH DIFFERENCE (Po), M; FRESNEL NO. (No)	4.90	2.00	2.81	1.46					4.81	.75	4.49	.83		
AB) BARRIER TRANSMISSION FACTOR (Fb)x(Do/15)-1	.0081	.016	.009	.014					.0041	.014	.0046	.013		
AC) OBSERVER DNSE(L) WITH BARRIER, PASQUES	.37	5.94	.04	.27					.19	5.19	.02	.25		
TOTAL DNSE (PASQUES)	6.62		OK						5.65		OK			

Figure 20. Examples of the procedure for scenarios 6 and 7.

Preliminary design of the barrier indicated the height requirement was 3.86 m for Db = 5 m and 4.64 for Db = 13.8 m. The trial design in Figure 20 was worked with the shorter 3.86-m barrier closer to the highway. It was assumed that its ends would be brought back to the right-of-way to minimize the length requirement (Figure 21). Final design should carefully examine the end requirement using the Complex Site method. Note: at most real sites, some shielding will exist that can be used to advantage in minimizing barrier lengths.

Initial Screen and Complex Site Methods, Scenario 8 (Figure 22)

The geometry for scenario 8 is illustrated in Figure 23. The distances and angles were scaled from this figure. It has 1000 Army trucks, 40 percent operating at night equally in both directions. It has a design goal of 100 pasques.

An Initial Screen was made for both observer sites using an assumed straightline extension of the highway section with most probable importance. The results show that the DNSE at observer site 1 is estimated as 172 pasques, whereas that at observer site 2 is estimated as 64 pasques. Because the model assumed for screening probably overstates the noise exposure by a factor of two, it is not necessary to perform a complex site analysis for this site. Such analysis is required for site 1, however.

The Complex Site method with an equivalent travel line of analysis was then used to estimate contributions by each of the four segments (the tunnel is assumed to have some sound absorption) so that no segment is necessary inside the tunnel. Because the extension of segment A ran close to the observer site (Do = 7.8 m, which is less than 15 m), the transmission factor was calculated by both standard and alternative methods for situations in which an extension is very close to the observer (Equation 25d). This latter result was both more accurate and lower, and was therefore used in summing the contributions to the DNSE at the observer site.

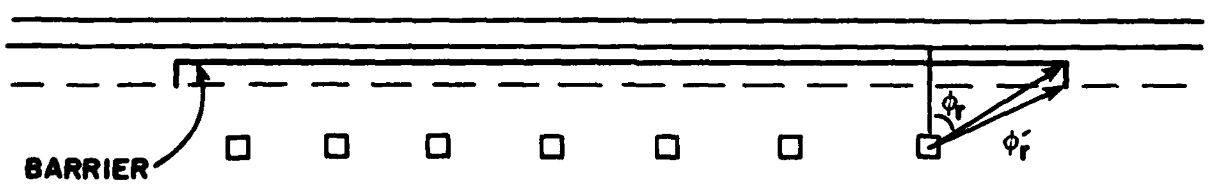
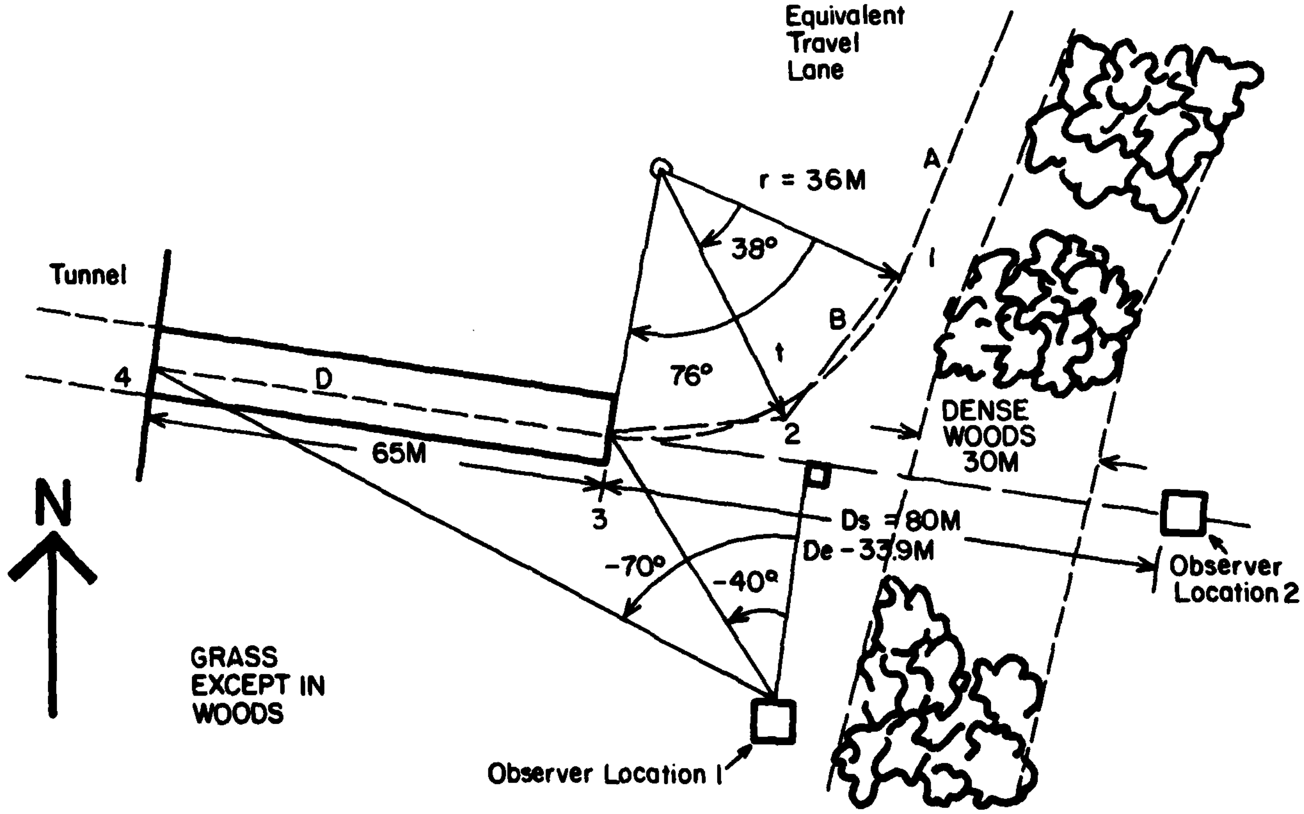


Figure 21. Use of barrier ends to maintain a large barrier angle without extending the barrier length unnecessarily.

ITEM	8. INITIAL SCREEN				8. OBSERVER 1, COMPLEX SITE (EQUIV.)								TOTAL
A) ROAD SEGMENT NO.; LANE IDENTITY	OBS.1		OBS.2		A		B		C		D		
B) DESIGN GOAL D/N SOUND EXPOSURE (DNSE), PASQUES	100				100								
C) VEHICLE TYPES (AA, AC, MT, HT, AT, TT AND TW)	AT		AT		AT								
D) VEHICLE VELOCITY, KMH	50		50										
E) SINGLE VEHICLE SOUND EXPOSURE (SE), PASQUES	0.1		0.1										
F) GRADIENT (Y OR N); VALUE (%); & NOISE FACTORS (Fu+Fd)	N		N										
G) AVG. NO. OF VEHICLES IN DAY (0700-2200) (Nd)	600		600										
H) AVG. NO. OF VEHICLES AT NIGHT (2200-0700) (Nn)	400		400										
I) AVG. EFFECTIVE NO. OF VEHICLES (Nd+10Nn)=Ne	4600		4600										
J) DIRECTIONAL TRAFFIC RATIO, 0.7<R<1.5 (Y OR N?)													
K) DIRECTIONAL VELOCITY RATIO, 0.8<R<1.2 (Y OR N?)													
L) PARTIAL D/N SOUND EXPOSURE AT 15 M, PASQUES	460		460		460		460		460		460		
TOTAL DNSE (PASQUES)													
M) OBSERVER DISTS. TO NEAR & FAR LANES (Df, Dn), M	28.8		43.3										
N) FAR, NEAR LANE DIST. RATIO, Df/Dn<=2 (Y OR N?)													
O) OBSERVER DIST. (Do), EITHER Df OR Dn, OR De	28.8		43.3		7.8X		22.9		40.4		33.9		
P) SEGMENT END ANGLES (ΘL & ΘR), DEG.					80.90		55.70		-26.6		-40.70		
Q) VEGETATION TRANSMISSION FACTOR (Kw)	1.0		.4		1.0		1.0		1.0		1.0		
R) BUILDING ROW TRANSMISSION FACTOR (Kh)	1.0		1.0		1.0	X ALT	1.0		1.0		1.0		
S) SHIELDING TRANSMISSION FACTOR (Ks)					1.0	USE	1.0		1.0		1.0		
T) BASELINE TRANSMISSION FACTOR (QxRxS) = Kc	1.0		1.0		1.0	↓	1.0		1.0		1.0		
U) GROUND ABSORPTION (a); ANGULAR PROP. FACTOR (Ka)	.72		1.0		.0167	↓	.045		.105		.0824		
V) TRANSMISSION FACTOR (SMALLER OF U & T)x(Do/15)$^{-1}$ = Ko	.38		.14		.032	.025	.029		.039		.0344		
W) OBSERVER BASELINE DNSE(L), PASQUES	172		63.7			11.45	13.46		18.03		16.77		
TOTAL DNSE (PASQUES)	172		63.7		59.71 OK								59.71
X) BARRIER DIST. TO SOURCE (Db), M			OK										
Y) BREAK DIST. IN LINE OF SIGHT (B), M													
Z) BARRIER END ANGLES (ΦL & ΦR), DEG.													
AA) PATH LENGTH DIFFERENCE (Po), M; FRESNEL NO. (No)													
AB) BARRIER TRANSMISSION FACTOR (Fb)x(Do/15)-1													
AC) OBSERVER DNSE(L) WITH BARRIER, PASQUES													
TOTAL DNSE (PASQUES)													

Figure 22. Examples of the procedure for scenario 8.



Note: $t = 36 \ \cos 76/2 + 76/57{,}312^2 - \sin^2 76/2$

$= 37.24$ M for defining segments B & C

Figure 23. Geometry for example 8 with Complex Site procedure.

6 CONCLUSION

A procedure has been developed for predicting vehicle noise and noise barrier performance with improved accuracy over previous methods. This procedure incorporates new source data and involves a new calculation technique using a linear measure of noise exposure. This technique will be incorporated in the Integrated Noise Contour System (INCS) to enable installations to perform accurate predictions of vehicle noise and to design effective noise barriers in-house.

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APPENDIX:

ANALYSIS OF ARMY VEHICLE NOISE EMISSIONS

Introduction

TM 5-803-2 contains nomographs for use in predicting the DNL noise levels adjacent to roadways and highways in and around military facilities. Specifically, this TM includes nomographs of the following vehicle categories: medium trucks, heavy trucks, transport vehicles (tracked), and weapon vehicles (tracked).

CERL surveyed typical military vehicles as part of an experiment developed for the U.S. Environmental Protection Agency (EPA) to judge human differentiation of vehicle types. In this special EPA measurement program, the vehicle noise emissions were recorded at distances of 15 and 30 m from the center line of vehicle travel. The vehicle was photographed for identification and its speed was measured using a radar gun.

In addition to the prediction nomographs contained in TM 5-803-2, the Federal Highway Administration has recently published similar nomographs for use by state highway departments and others in the vicinity of highways. These procedures include nomographs for the prediction of the equivalent level (Leq) resulting from heavy and medium truck traffic.

Discussion

Before looking at the data gathered by CERL on Army vehicles, it is useful to first compare TM 5-803-2 predictions with those of the Federal Highway Administration. Figure A1 compares the Federal Highway Administration predictions for heavy and medium trucks with the TM predictions.* Comparing these figures shows close agreement between the TM and the Federal Highway Administration predictions for noise emissions of medium trucks, but the comparison for heavy trucks is less than satisfactory.

Figure A2 shows the CERL-measured data. These data appear to divide into two categories (although much more data would be required to substantiate this point). This division most likely reflects the two types of engines currently used in military vehicles: multi-fuel and pure diesel.

Figure A3 shows the CERL-measured data superimposed on Figure A1. From this figure, it is clear that the two divisions to the CERL-measured data parallel the medium truck data and the Highway Administration heavy truck data, rather than the TM heavy truck curve.

*The data portrayed in this figure are for "hard sites," or sites for which the measurements are made over a hard reflecting surface such as asphalt or concrete rather than where a grassy stretch exists between the highway and the microphone. (The Federal Highway Administration predicts a reduction of 1.7 dB for a soft site.)

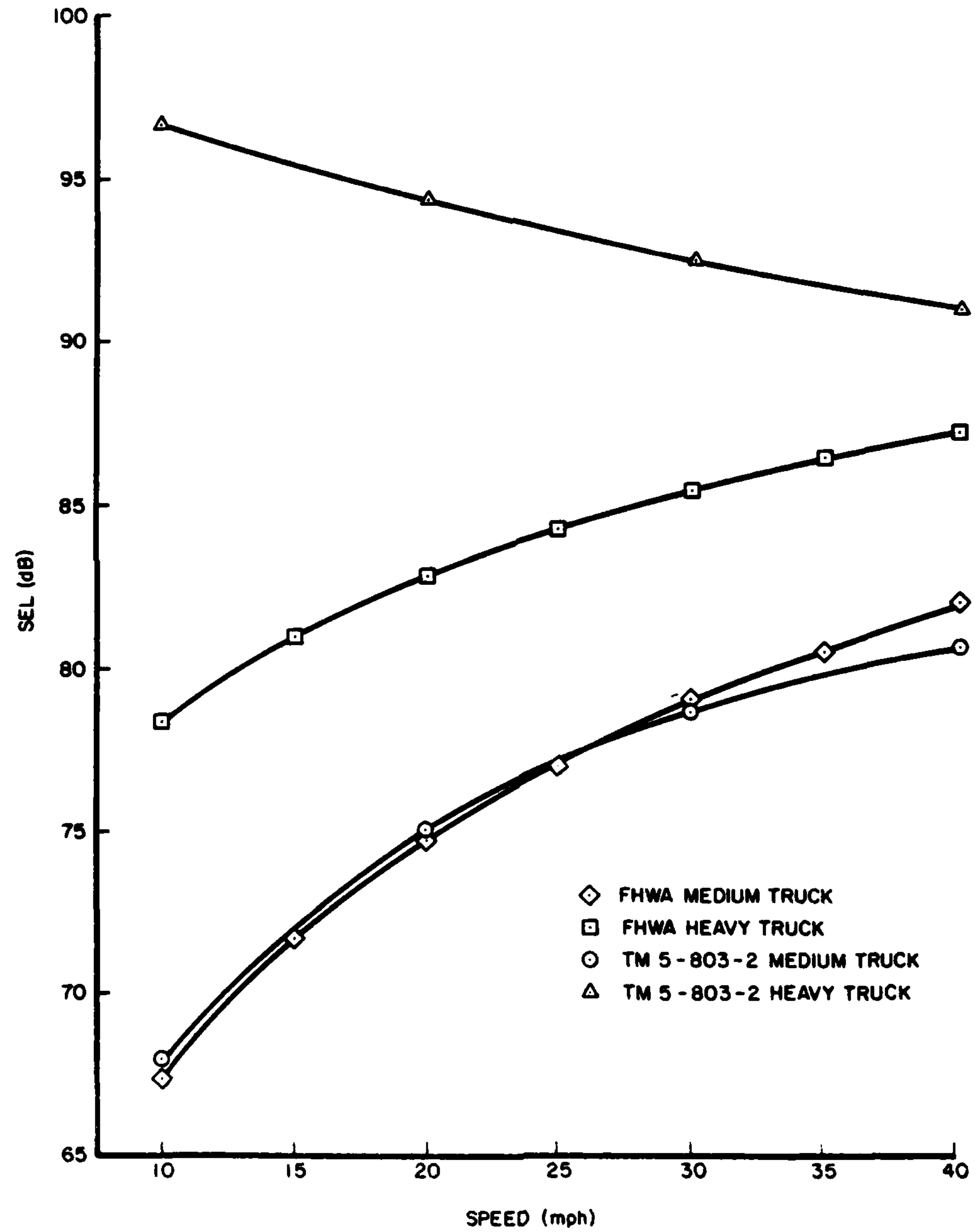

Figure A1. Comparison of the FHWA Highway Traffic Noise Prediction Model with the TM 5-803-2 nomograph for medium and heavy trucks. (Note the large difference for heavy trucks.)

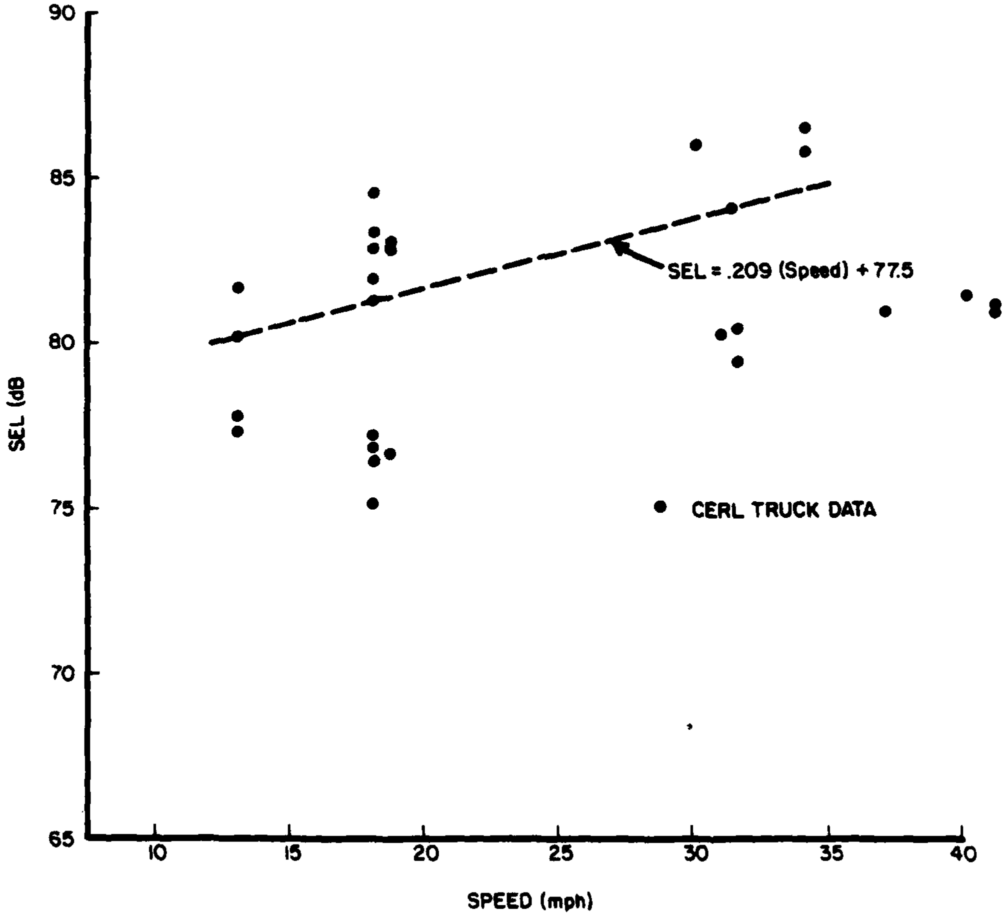

Figure A2. CERL-measured data. The dotted line represents an approximate energy average of the data.

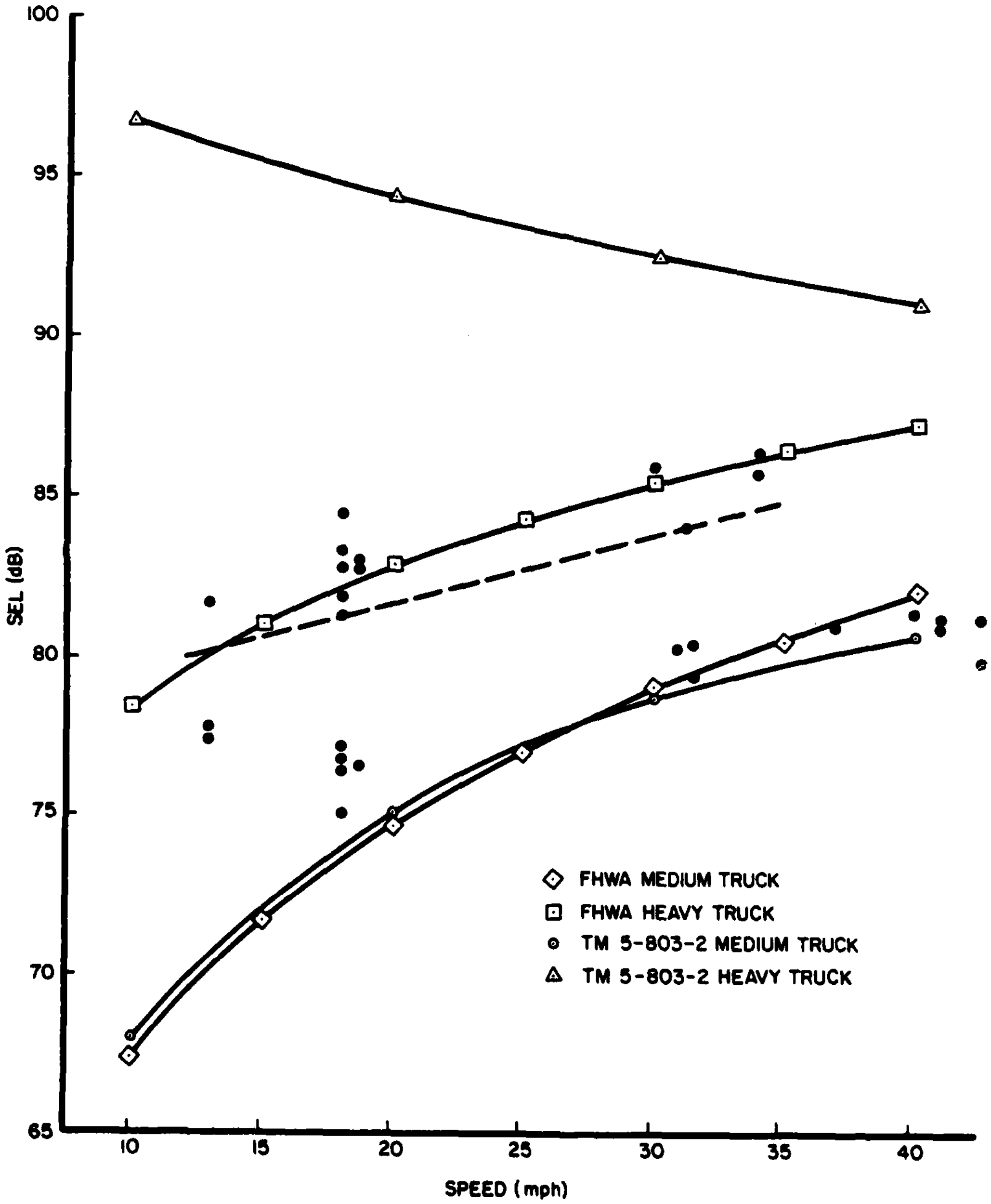

Figure A3. CERL-measured data compared with FHWA and TM 5-803-2 predictions for heavy and medium trucks.

The CERL-measured data can be approximately replaced with the simple dotted curve also shown in Figure A3. This curve is derived as an energy average curve fit to the CERL-measured data. The dotted curve shows (at least for these limited data) that Army trucks in general can be approximated by the medium truck curve in TM 5-803-2 supplemented by a constant of 7 dB. It is recommended that this value be used for planning and assessment until more data can be produced that further amplify and clarify these points.

Figure A4 shows the TM 5-803-2 curves developed for transport and weapon vehicles. Also plotted on this figure are the CERL-measured data for these vehicle categories. A general agreement exists between the transport vehicles and the TM curve. However, at low speeds, the weapon vehicles (self-propelled guns and tanks) appear to lie somewhat above the TM curve. That is, the TM predictions tend to underestimate the noise of these vehicles operating at low speeds. Since these vehicles typically travel at lower speeds in cantonment areas, it is suggested that 5 dB be added to the TM predictions to account for this underestimation.

Conclusions

1. To model all Army trucks, use the TM 5-803-2 curve for medium trucks and add 7 dB to the result.

2. To model weapon vehicles (tracked), use the corresponding TM 5-803-2 curve and add 5 dB to the result.

3. To model transport vehicles (tracked), use the TM 5-803-2 curve for them.

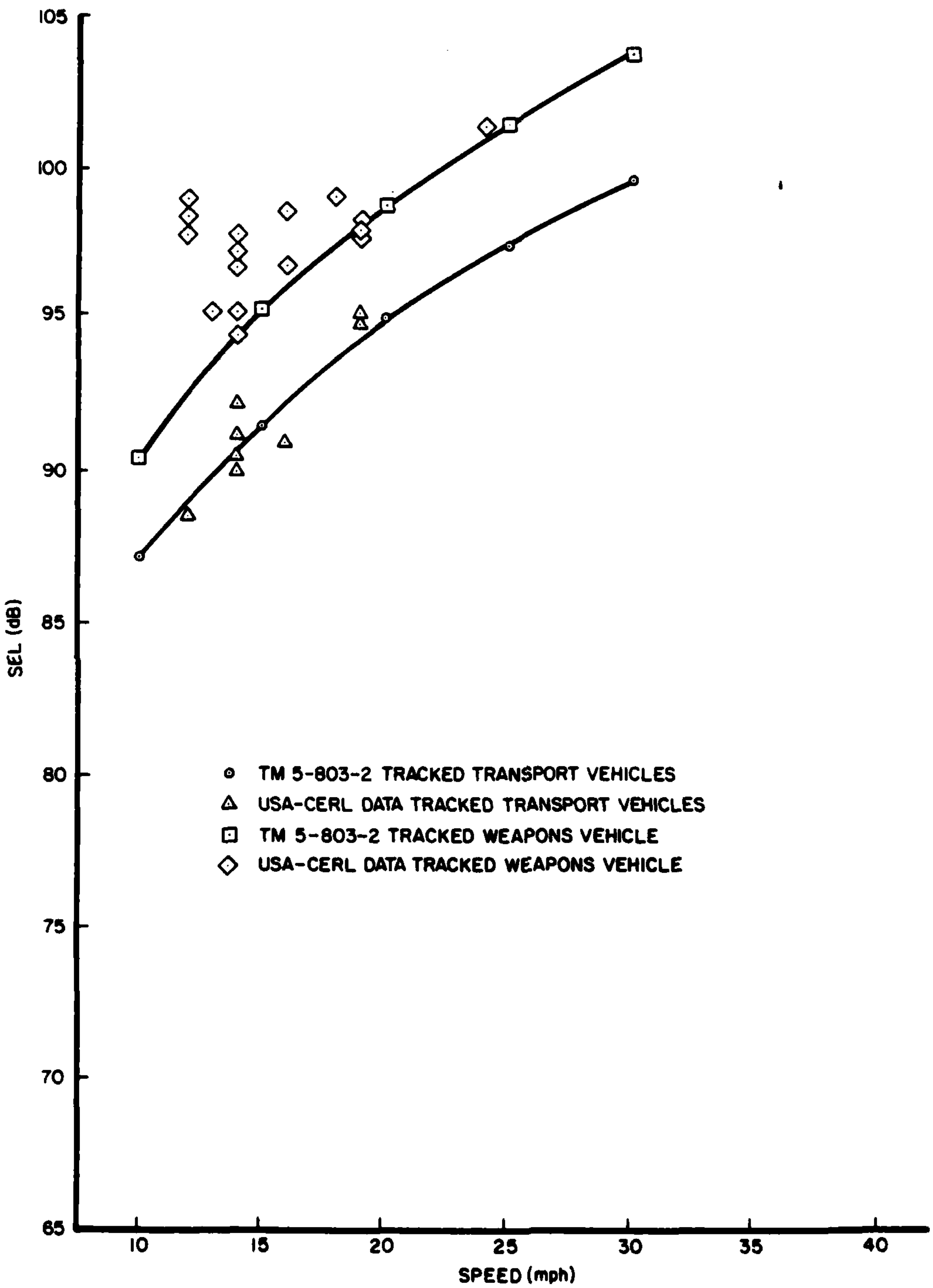

Figure A4. CERL-measured data compared with TM 5-803-2 predictions for transport and weapon vehicles (all tracked).

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USA ARRADCOM 07801
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Ft. Clayton, Canal Zone 34004
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Ft. Detrick, MD 21701

Ft. Leavenworth, KS 66027
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Naval Air Systems Command 20360

US Naval Oceanographic Office 39522

Naval Surface Weapons Center 22485
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AF/LEEEU

Patrick AFB, FL 32925
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Tyndall AFB, FL 32403
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Wright-Patterson AFB, OH 45433 (3)

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Transportation Research Board 20418

Dept of Housing and Urban Development 20410

Dept of Transportation Library 20590

Illinois EPA 62706 (2)

Federal Aviation Administration 20591

Federal Highway Administration 22201
Region 15

NASA 23365 (2)

National Bureau of Standards 20234

Office of Noise Abatement 20590
ATTN: Office of Secretary

USA Logistics Management Center 23801

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